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AUG 77 J E NANEVICZ, R C ADAMO, R T BLY NAS9-15101
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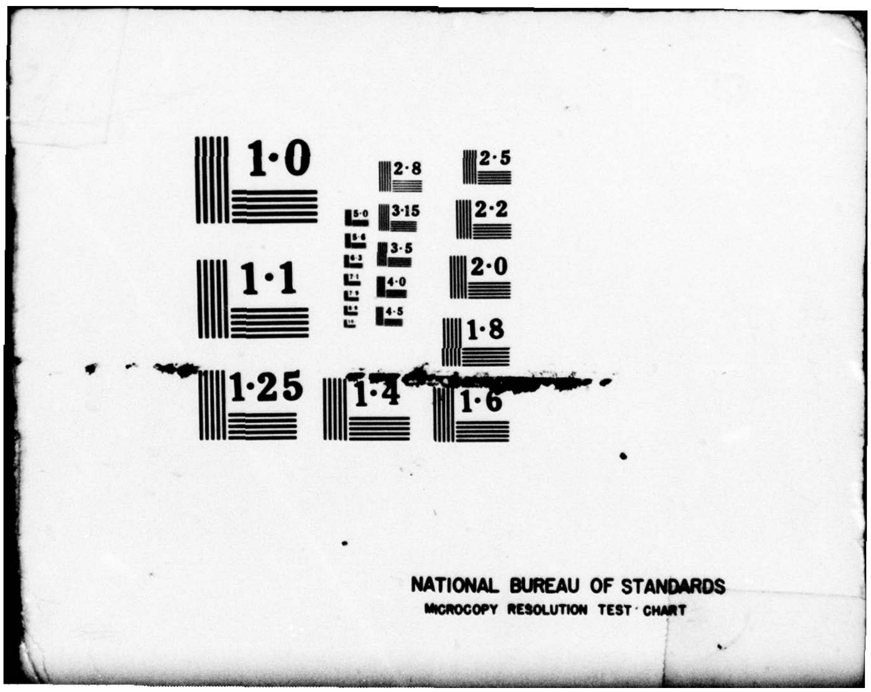
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AIRBORNE MEASUREMENT OF ELECTROMAGNETIC ENVIRONMENT NEAR THUNDERSTORM CELLS (TRIP-76)

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA 94025

AUGUST 1977

TECHNICAL REPORT AFFDL-TR-77-62
Final Report

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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This report has been reviewed and is approved for publication.

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The increasing use of digital equipment and nonmetallic structures on aerospace vehicles has focused new attention on the potential electromagnetic threat posed by the lightning and thunderstorm environment. To better define this threat, a quick reaction airborne lightning measurement effort was undertaken, jointly by AFFDL, NASA, and Stanford Research Institute, ~~under contract, during~~ the TRIP-76 program conducted near Kennedy Space Center. Digital 'snapshot' data and continuous analog spectrum analyzer data were alternately recorded on an instru-

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20. (cont'd) mented NASA Learjet during 29 flights, between 6 July and 12 August 1976. Recorded events included one direct lightning strike and many nearby strikes, as well as "incipient lightning" streamers and non-lightning-associated signals. A comparison with nuclear EMP waveforms is given, indicating nearby lightning to be a far more energetic threat than EMP at low frequencies, and that it is non-negligible at 10 MHz and above. A first order analysis of expected internal wiring currents induced by the direct strike is also provided, which agrees with measured values. During this program the aircraft was struck by lightning at an altitude of 37,000 ft., and sustained damage to the nose radome and pitting of the aft end of the right wing tip tank. The associated ambient electric field approached the criterion for triggering of a lightning strike given by E. T. Pierce (field strength $\gtrsim$10 KV/m, potential discontinuity $\approx 10^6$V), and suggests the Learjet may have triggered the strike. Nearby lightning was found to generate internal aircraft transients of magnitudes comparable to those of the direct strike (within a factor of 2). This indicates that the probability of encountering nearby lightning, in addition to the probability of suffering direct strikes, should be used in assuring electronic system integrity in an all-weather environment. Considerable variation in the high frequency characteristics of successive components of a flash was observed. "Incipient lightning" streamers - an incomplete initiation of triggered lightning - is one explanation for a periodic series of noise pulses observed with prominent 1 MHz energy on external and internal antennas, in association with a build and abrupt fade of ambient noise in the 1-30 MHz range. Another possible explanation is passage of the aircraft through inhomogeneities in the electric field structure. Other signals thought to be associated with electrification of the aircraft itself were also observed. Overall results define the need for additional airborne measurements. Simultaneous spectrum analyzer and transient digital recordings should be made for external fields and internal transients and for aircraft skin currents. The "incipient lightning" effect should be investigated, and accurate waveforms obtained for k-streamer, inter-stroke electrical processes. Statistical descriptions of rise time, duration, peak current, and similar parameters of the sort obtained by Cianos and Pierce for cloud-to-ground events, should be derived for these phonomena.

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I INTRODUCTION

A. Background

For the past several decades, aircraft have generally been fabricated with all metal skins. Skin material and thickness have been determined by structural requirements. In general, it has been found that material, thickness, and fabrication techniques were such that, in the past the aircraft could pass lightning stroke currents with relatively minor damage--usually pitting and puddling of the skin at the stroke attachment points. Occasionally it was necessary to provide additional skin thickness in critical regions such as fuel cells at wing extrimities. In addition, metal skins have served to shield interior systems from interference signals generated by precipitation static, nearby lightning, and direct lightning strikes.

Initially, electronic systems used on aircraft employed high-level analog circuitry which was tolerant of occasional noise pulses of considerable amplitude. Presently, solid state electronic systems operating at low signal levels are common. These systems suffer component damage and upset at much lower levels. Ultimately it is planned that all avionic systems will be completely digital, operating at low signal levels. Experience with a variety of digital systems indicates that they are susceptible to catastrophic upset as the result of a single impulse at a level comparable to the system operating level.

Presently, aircraft are being fabricated with many of their complex, non-load-bearing surfaces made of fiberglass. In the future, it is planned that, for reasons of strength and weight, large sections of aircraft skin and structure will be made of composite materials. These non-metallic regions are not suitable for conducting lightning stroke currents and do not provide the RFI shielding formerly obtained with metal structures. Accordingly, programs are currently under way to devise techniques such as coatings to improve the electrical and shielding properties of composites.

Since the skin on an all-metal aircraft is needed for aerodynamic and structural reasons, no penalty is imposed in providing current conduction capability and electromagnetic shielding, and it is quite likely that most aircraft are overdesigned in these regards. If, on the other hand, it becomes necessary to apply special processes to achieve current-handling and shielding, their implementation imposes a cost penalty--weight, initial cost, and increased maintenance cost. Accordingly, the designer is in the position of requiring accurate information regarding the physical processes for which he is endeavoring to provide protection in order that he neither overdesign nor underdesign.

In the past, airplane designers have been concerned almost exclusively with problems associated with damage generated by direct strikes to the aircraft. For this work, a "standard" stroke has been developed which duplicates in the laboratory the damage observed on actual strikes to aircraft. It is evident that strike damage can be duplicated with considerable accuracy even when certain features of the strike (such as the higher frequency components) are poorly simulated. Thus the "standard" stroke specifies such parameters as rise time, peak current and decay time without much regard for processes associated with the formation of the stroke. This procedure has the result of providing a useful simulation of the low-frequency features of the stroke.

In approaching the problem of signals coupled into the interior of the aircraft, on the other hand, the high-frequency components of the source are of great importance. Information regarding the high frequency components of lightning is almost entirely confined to data obtained from ground-based measurements. To apply these data to the case of a lightning flash near an aircraft, it is necessary to carry out a substantial number of calculations to properly account for the rate of decay with distance of the various components of the stroke. Also, it is not clear that the ground-based measurements adequately account for all of the nonlinear processes involving the presence of the aircraft. As the result of these observations, it was felt that in-flight measurements of lightning source parameters would be highly desirable.

B. 1976 Learjet Tests in Florida

In June 1976, it was established that Learjet 705 owned by NASA Ames would be operated in Florida during the peak of the thunderstorm season to investigate the electrostatic characteristics of thunderstorms forming in the vicinity of Kennedy Space Center (KSC) with particular attention to the region of the thunderstorm anvil. Experience during the 1975 Florida thunderstorm studies using the Learjet indicated that the aircraft spent large amounts of time in the vicinity of thunderstorm cells at altitudes ranging from 20,000 to 45,000 ft. Since the Thunderstorm Research International Program II (TRIP) involving a large number of atmospheric electricians and lightning experts was also to be underway at KSC during the peak of the thunderstorm season, it was possible that the same cells might be studied from the ground by the TRIP investigators and in the air by the Learjet.

To take advantage of the availability of the Learjet and its static field instrumentation, a modest, quick-reaction program was initiated by the Air Force to install suitable instruments on the Lear to permit simultaneous measurement of the electromagnetic transients associated with nearby lightning. The transient study program had a number of objectives that can be summarized generally as follows:

- **Provide information regarding the lightning transient source from the vantage point of an aircraft.**
- **Study the interaction of the aircraft with its environment in the vicinity of thunderstorm cells.**
- **Measure signals induced by lightning flashes in wiring on the inside of the aircraft.**
- **Gain experience regarding the capabilities and limitations of modern instrumentation in making flight test measurements of lightning effects.**
- **Generate inputs and recommendations regarding the design of future tests.**
- **Assess the usefulness and limitations of ground-based measurements in describing lightning effects on aircraft.**

II INSTRUMENTATION

A. Learjet Test Aircraft

The Learjet 24B NASA 705, owned by NASA Ames and instrumented for use on this program, is ideally suited for thunderstorm studies. This aircraft has a service ceiling of 45,000 feet, a cruising speed of 464 knots, a rate of climb of 6,800 feet/minute, and can accommodate a two-person crew and three passengers in addition to instrumentation.

The Learjet's agility and speed allow considerable data to be collected throughout a large volume of space in the region surrounding a thunderstorm during the entire process of storm formation and development. During this program, measurements were made of the static electric-fields in the vicinity of thunderstorms and of the electrical transients produced both external to and internal to the aircraft by nearby lightning.

B. Static Electric-Field Measurement Instrumentation

The presence of an aircraft in an electric-field perturbs the field in such a way that the fields measured at points on the aircraft surfaces are different from the free-space fields that would exist if the aircraft were not present.

The electric-field measurement system installed on the Learjet was therefore designed to readily allow the reconstruction of the free-space field components from the measured aircraft surface fields.

The scalar field magnitude measured at a point on the aircraft surface represents the magnitude of the field perpendicular to the surface at that point, but is, in general, the result of the three-dimensional free-space field with a possible additional offset produced by a non-zero potential on the aircraft itself. Thus, in order to determine the magnitudes of the three free-space field components, four independent scalar measurements are required.

Four compact rotating vane electric-field sensors were therefore installed on the Learjet test aircraft. The locations of these sensors are shown in Figure 2-1. These locations were chosen to appropriately maximize the coupling between the sensors and the free-space field components within the constraints imposed by structure, access, cabling, and aerodynamic considerations.

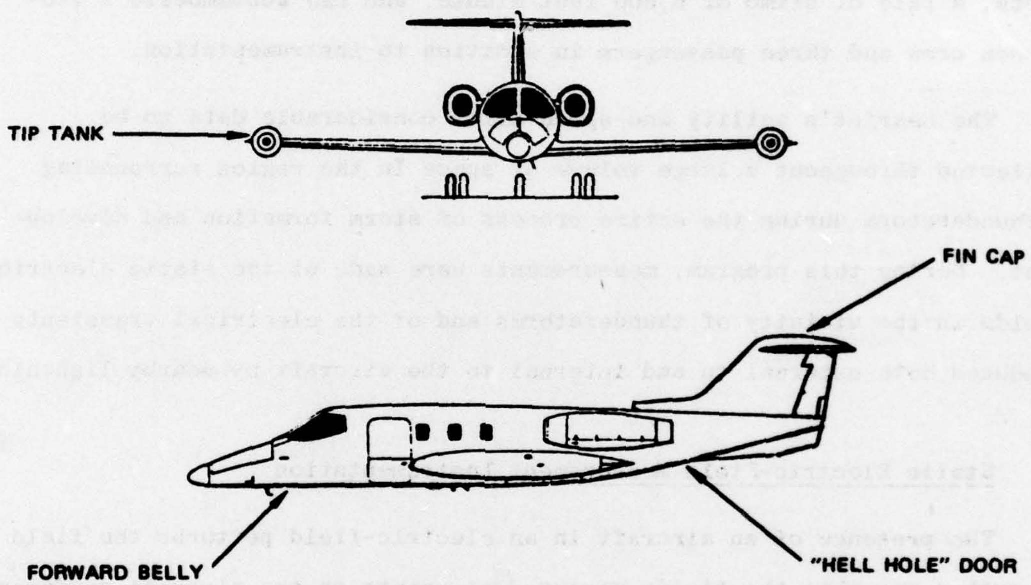


FIGURE 2-1 LOCATIONS OF FIELDMETER SENSORS ON NASA LEARJET TEST AIRCRAFT

The relationship between the measured electric-field magnitudes and the four quantities to be determined (i.e., the three free-space field components and the aircraft potential) was determined using scale-model measurement techniques.

In order to provide real-time outputs of the desired quantities, the onboard instrumentation package included an analog signal processor designed to solve the resulting system of linear equations.

Figure 2-2 is a block diagram of the onboard electric-field measurement system.

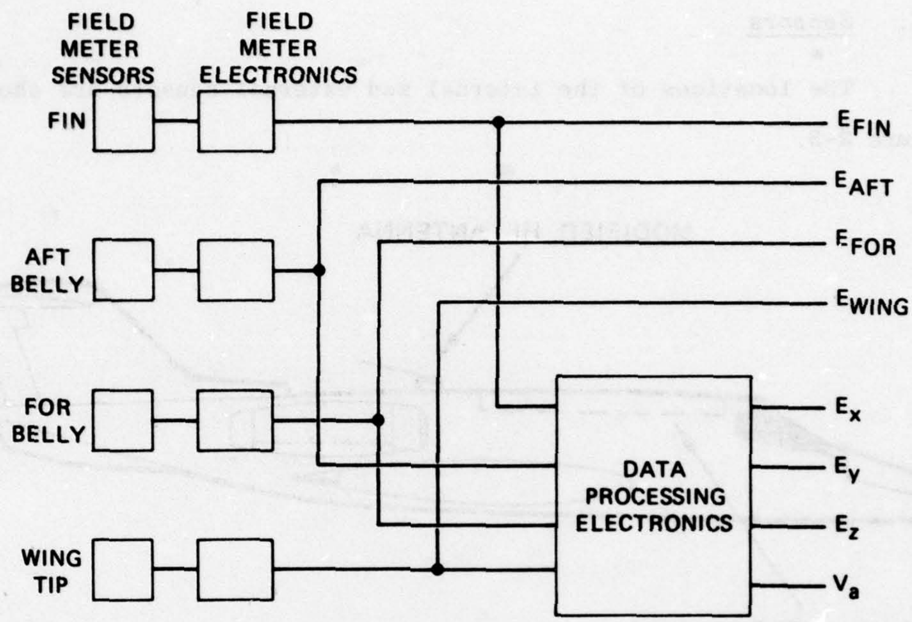


FIGURE 2-2 BLOCK DIAGRAM OF NASA LEARJET FIELD MEASURING ELECTRONICS

The electrical outputs of this system were continuously recorded on an analog strip-chart recorder and simultaneously displayed on a set of analog meters for real time interpretation by the system operator.

The measurement ranges of the system were from a few hundred volts/meter to 75 kV/meter for each of the three field components and from 1 kV to 375 kV for the aircraft potential.

C. Electrical Transient Measurement Instrumentation

In addition to the electric-field measurement system, an electrical transient measurement instrumentation system was installed in the Learjet test aircraft. The purpose of this system was to measure the natural atmospheric electrical environment outside the aircraft resulting from nearby lightning, as well as electrical transients induced within the aircraft by the external lightning environment.

1. Sensors

The locations of the internal and external sensors are shown in Figure 2-3.

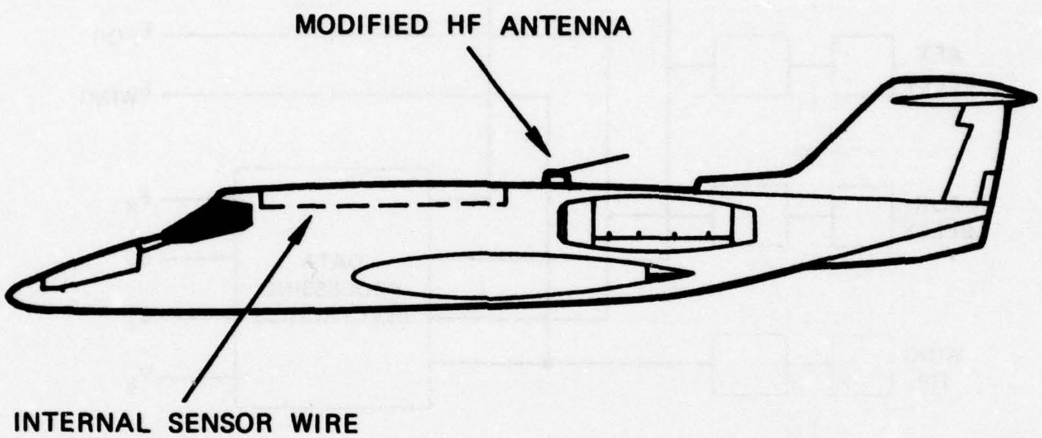


FIGURE 2-3 LIGHTNING PULSE SENSORS ON NASA LEARJET TEST AIRCRAFT

The external sensor used throughout this program was fabricated by modifying an HF antenna already existing on the aircraft. This electric-dipole-antenna was coupled to the instrumentation system through a wide-band switchable gain preamplifier that was mounted inside the aircraft directly below the antenna feedthrough.

A magnetic-loop antenna, which has the advantage that it is less affected by sudden changes in airplane potential caused by tribo-electric charging, was prepared for use during the last few days of flight tests. It was not installed since, in general, satisfactory results were being obtained with the existing electric-dipole, and it was not felt that undertaking the installation of a new antenna was warranted during the last few days of the program.

In addition to the external sensor, Figure 3 shows the location of the internal transient sensing antenna. This antenna consisted of a single unshielded wire or, at times, a twisted pair of unshielded wires strung inside the airplane and approximately 5 inches from the ceiling from a convenient mounting point just behind the cockpit to another mounting point approximately 9 feet toward the rear of the cabin. Provisions were made for terminating each of the wires with an open or short circuit or with any desired resistance.

Currents or voltages on the internal wire antenna were detected using a Tektronix CT-2 current probe. The outputs from the current probe were fed directly to the transient measurement instruments.

Two different types of electrical transient measurement instrumentation systems were used at different times to process the signals detected by the internal and external sensors.

2. Transient Digitizer

During one portion of the flight test program, the AFFDL transient digitizing instrumentation system, as shown in Figure 2-4, was used. At some times this system was connected to the wideband preamplifier to monitor external lightning induced transients. At other times the system was used to monitor transient signals induced in the internal wire antenna. A brief description of this system abstracted from Ref. 9 appears below.

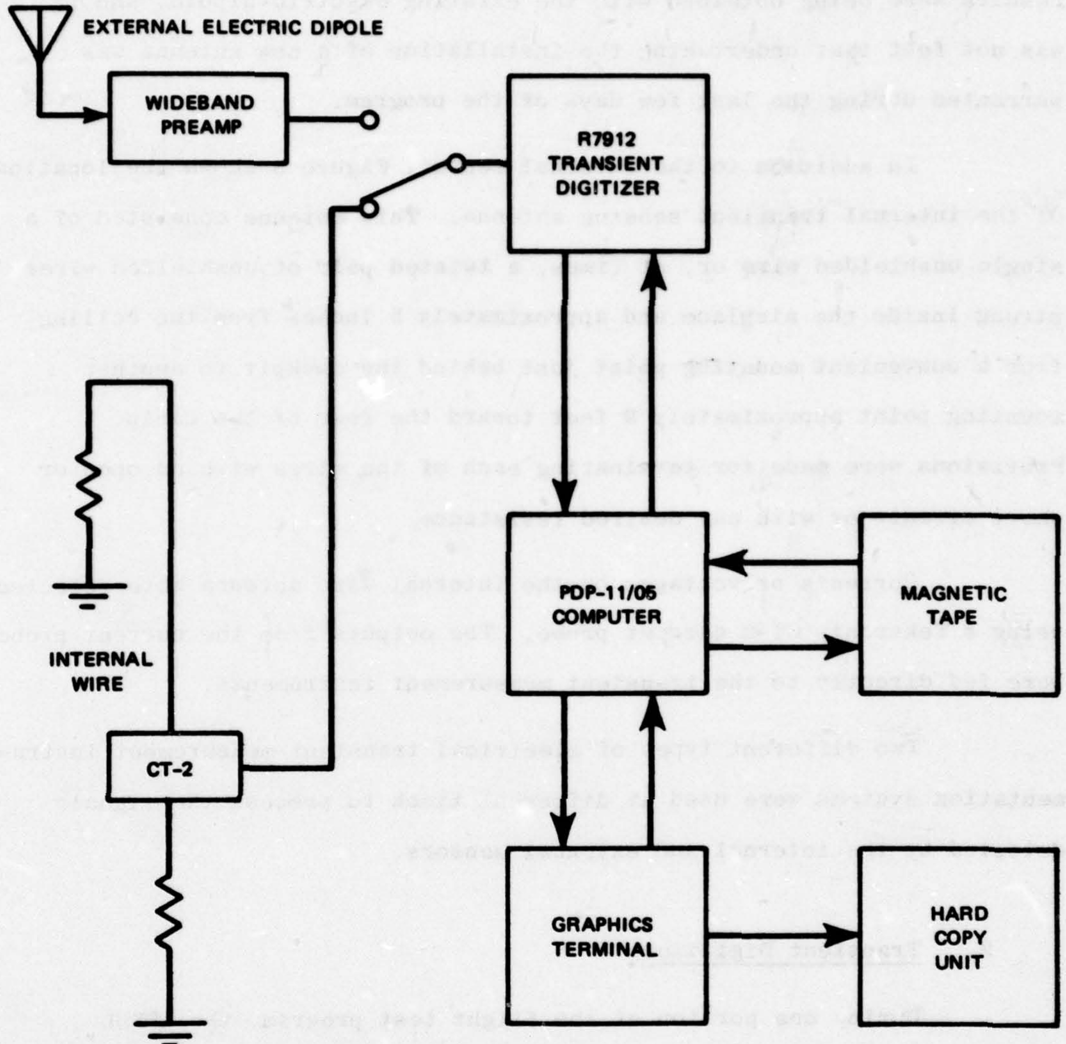


FIGURE 2-4 TRANSIENT DIGITIZING INSTRUMENTATION SYSTEM

<u>R7912 Transient Digitizer</u>. The Tektronix R7912 Transient Digitizer is a high-speed analog-to-digital converter which can sample at rates up to 1 GHz. It has the capability of storing raw data in an array of up to 4096 9-bit digital words with a resolution sufficient to discern 512 distinct vertical levels in each sample.

The R7912 is operated much like an oscilloscope, with the exception that its output can either be viewed on a TV monitor or diverted directly to the minicomputer. For handling by the minicomputer, the raw data array is reduced to an array of 512 elements or samples. The transient waveform is subsequently processed and stored in this form.

During these tests, the R7912 was operated with a combination of vertical amplifier and horizontal time base that resulted in an upper bandwidth for the digitizer system of 500 MHz. The lowest sweep speed that could be used with the flight system was 1 ms/division.

Minicomputer. The PDP-11/05 computer forms the hub of the Waveform Digitizing Instrumentation and makes possible the operation of the various devices as an instrumentation system. When not being used to control the Transient Digitizer, the computer can also be used (with its BASIC language compiler) to perform normal computational tasks.

The system operates under control of a standard Tektronix software package. All communications with the digitizing hardware is accomplished within this software. In addition to normal programming, the software has essentially all the capabilities of BASIC language compilers for other computer systems, with the addition of several very powerful commands of specific value in waveform processing.

Peripherals. Input/output for the digitizing system is handled by three units. Real-time operator communication with the system is accomplished with a Tektronix 4010-1 Graphics Terminal having alphanumeric and graphics capability, while the Tektronix 4610 Hard Copy Unit can provide permanent paper copies of information displayed at the terminal. The CP100 dual cassette drive provides a means of storage and retrieval of programs, data files, and waveform files using magnetic tape cassettes.

System Operation. Figure 2-4 represents the operation of the individual units comprising the transient digitizing instrumentation. During the in-flight test, all induced transient measurements were made by RG-58 coaxial cables which coupled into the R7912 from the antenna or the test circuitry being monitored. With the use of the computer, the measured information was displayed, analyzed, printed, and stored in real-time, reducing the requirement for later data processing of the stored waveform data.

A description of data obtained during the portion of the flight test program in which the transient digitizing system was used, is given in Chapter V, Section C.

3. Multi-Channel Spectrum Analyzer

For the remainder of the flight test program, the transient digitizing system was removed from the test aircraft, and replaced by the transient pulse measurement system shown in Figure 5.

The transient pulse measurement system consists basically of two independent four-channel discrete-frequency spectrum analyzers and a continuously-recording wide-band analog tape recorder.

As is shown in Figure 2-5, the signals induced in the internal and external sensors were simultaneously monitored using narrowband (20 kHz) filters centered at discrete frequencies of interest (1, 3, 10, and 30 MHz). The outputs of these filters were amplitude detected and recorded. The recorded data therefore provides a continuous measure of the energy within a 20 kHz band centered around each of the filter center frequencies. Two additional data channels were used to monitor the signals induced in the external sensor. One of these channels was used to record the output of the wideband preamplifier directly. The upper cutoff frequency of this data is therefore limited by the 20 kHz tape recorder

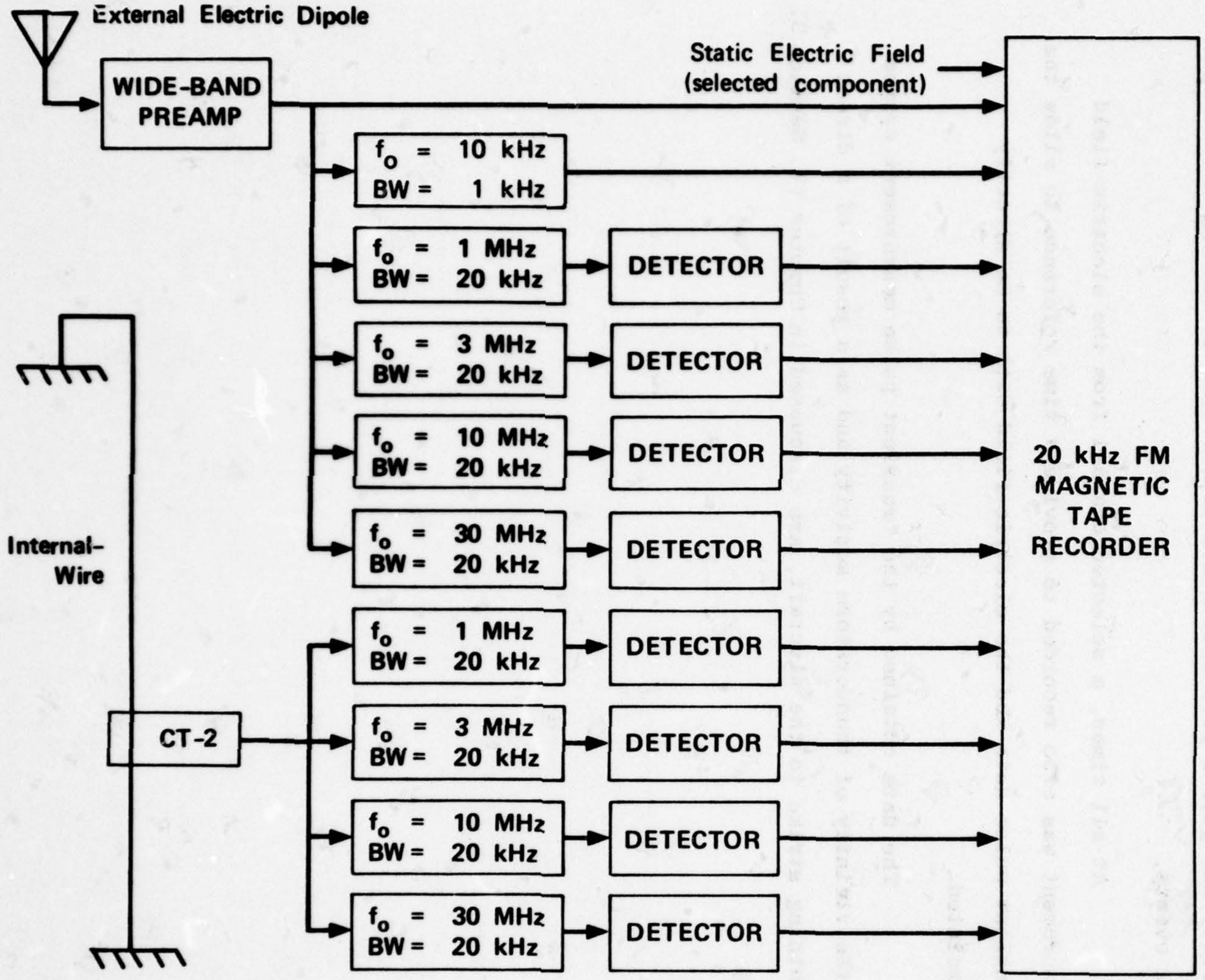


FIGURE 2-5 BLOCK DIAGRAM OF LEARJET TRANSIENT-PULSE MEASUREMENT SYSTEM

bandwidth. The other additional channel contained a 1 kHz bandwidth filter centered at 10 kHz. The output of this filter was recorded directly and gave a good indication of the time of occurrence of lightning events.

At all times, a selected channel from the electric-field measurement was also recorded to provide a time reference to allow the transient pulse data and the electric-field data to be directly correlated.

The data obtained by the transient pulse measurement system in the vicinity of thunderstorm activity and as a result of a direct lightning strike to the aircraft, are discussed in Chapter IV, Section B.

III FLIGHT TESTS

A. General

During the summer of 1976, the Static Electric Field Measurement System was successfully flown on 24 days between 6 July and 12 August. During this period there were 29 flights including a total of 300 passes near active thunderstorms that provided useful data.

The Transient Measurement Instrumentation was flown on 16 of the 29 flights.

B. Transient Digitizer Flights

The AFFDL Transient Digitizer was operated during 9 flights on 7 days between 13 July and 23 July. During this period approximately 190 waveforms were recorded. A preliminary analysis by AFFDL indicates that over 70% of these waveforms provide useful data.

C. Spectrum Analyzer Flights

The SRI-built Discrete Frequency Spectrum Analyzer was operated during 7 flights on 6 days between 5 August and 12 August. During this period, approximately 100 successful passes were made in the vicinity of active thunderstorms. The Spectrum Analyzer System was operated and recording continuously during each of these passes. More than 150 minutes of continuous data were therefore obtained in the vicinity of storm systems.

These data cover numerous periods during which nearby lightning was observed, and, in fact, during a pass on 10 August the aircraft

suffered a direct lightning strike while the Spectrum Analyzer System was in operation.

IV TEST RESULTS

A. General

As was indicated earlier, the spectrum analyzer system and the transient digitizer system were flown one at a time on the Learjet aircraft during summer 1976. Accordingly, it is not possible to make comparisons of simultaneously-generated data. However, since the aircraft was flown under generally similar meteorological conditions when either system was installed, it is reasonable to expect that the two systems were exposed to similar electromagnetic environments. Thus it is valid to make general comparisons of the data generated by the two systems.

B. Spectrum Analyzer

1. Lightning Strike

Perhaps the most dramatic event that occurred during the test program was the lightning strike to the aircraft on 10 August. Figure 4-1 shows the tracks flown around the thunderstorm under investigation. (The letter R with subscript indicates the run number). The techniques used to make measurements all about the storm and in the anvil is evident from the figure. It should be noted that, during the 1976 tests, the aircraft frequently passed through regions of precipitation in the anvil and in the general area of the tops of the cells. On run 8 when the aircraft was passing between the main set of cells and a single cell developing to the right, it was struck by lightning. The stroke attachment points on the aircraft were the nose radome which was damaged, and had to be replaced and the aft end of the right wing tip fuel tank which was burned and pitted.

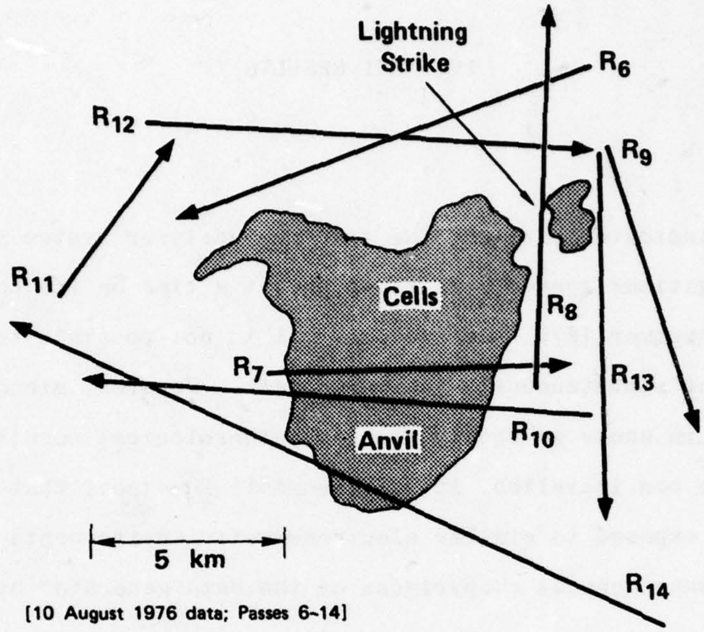


FIGURE 4-1 TYPICAL FLIGHT TRACKS AROUND THUNDERSTORM

A record of the static electric field readings recorded during run 8 is shown in Figure 4-2. Also shown in the figure is a rough sketch of the weather radar display showing a storm cell on each side of the aircraft.

The magnitude and direction of the ambient static field prior to the strike (≈ 70 kV/m directed along a line 15° to the left of the aircraft roll axis and elevated 47° above the horizontal) should be noted in the light of E. T. Pierce's criterion for necessary conditions that a conducting body trigger a stroke.[1*] Pierce observes that lightning is normally not triggered unless the ambient field is on the order of

*References are listed at the end of the report.

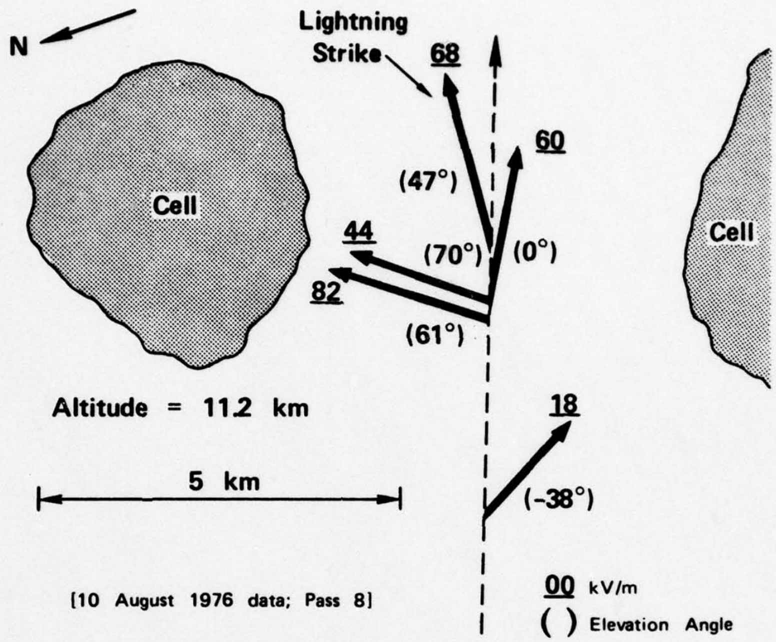
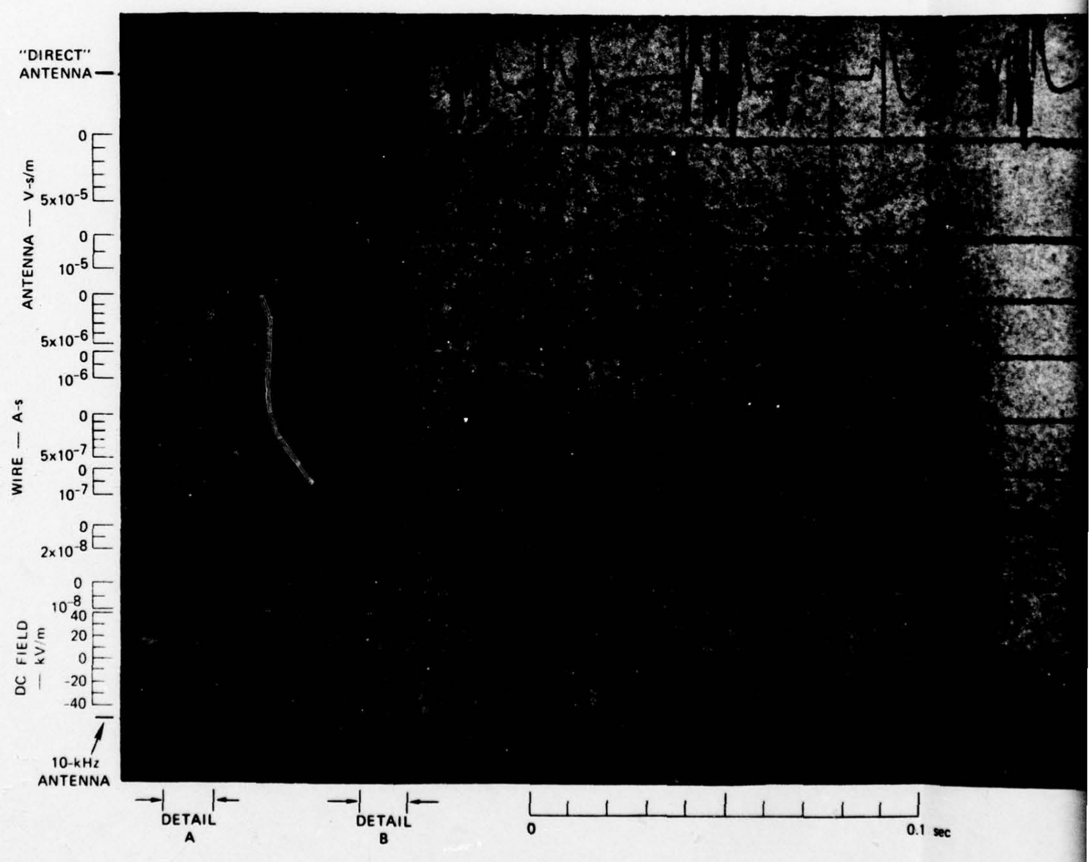


FIGURE 4-2 ELECTRIC FIELD VECTORS OBSERVED ON A PASS DURING WHICH THE AIRCRAFT WAS STRUCK BY LIGHTNING

10 kV/m and the size of the body is such that it produces a potential discontinuity of roughly 10^6 volts. The overall length of the Learjet is 13.2 meters so that the aircraft shorted out a total potential of 924 kV. Thus it is possible that the rapid introduction of the aircraft into the region of high electric field triggered the stroke.

The spectrum analyzer record for the overall period of the 10 August lightning strike is shown in Figure 4-3. The nomenclature of the various output channels becomes evident from reference to Figure 2-5. The top 5 records in Figure 4-3 were generated by spectrum analysis of signals induced in the electric dipole antenna on the top of the fuselage.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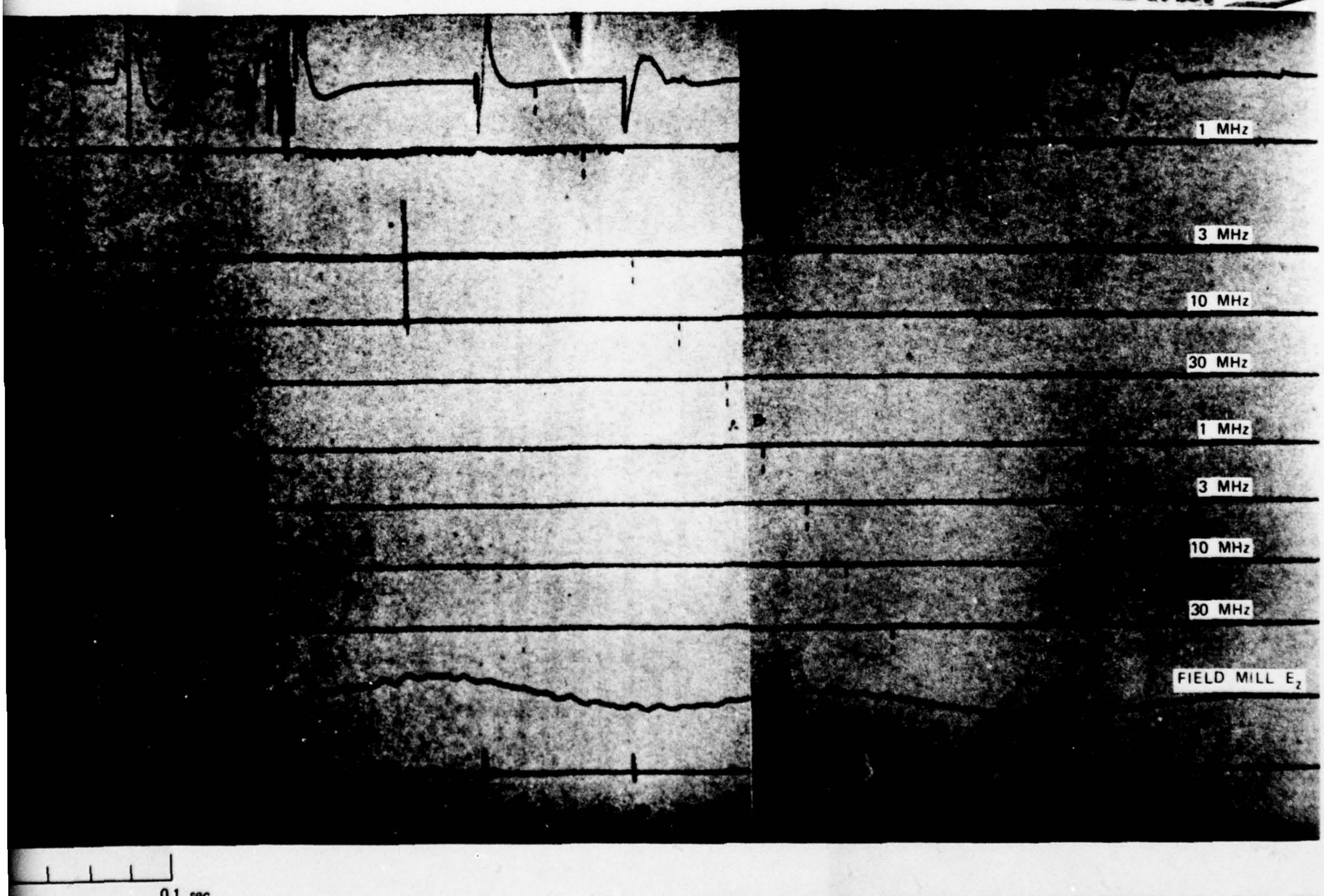

FIGURE 4-3 RECORD OF LIGHTNING STRIKE TO LEAR JET

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The next 4 channels are records generated by spectrum analysis of the short circuit currents induced in the wire on the roof of the interior of the fuselage. Second to the bottom in Figure 4-3 is a record of the vertical component of the electrostatic field about the aircraft. The bottom record is the response of the 10 kHz tuned circuit coupled to the electric dipole antenna. It should be noted that all of the 1 to 30 MHz channels include detectors in their outputs so that their outputs are unidirectional records of the envelope of the filter output. The 10 kHz channel is simply a high-Q filter so that its output in response to a transient input is a bi-polar ringing signal.

The disturbance associated with the flash, including the time when signals are induced in the inside wire, persists for roughly 0.5 sec. It is also evident from Figure 4-3 that the electromagnetic field at the location of the dipole is quite complicated. Bursts of noise (most prominent in the direct, 10 kHz, and 1 MHz channels) are interspersed with short, high-amplitude noise pulses on all channels. It is also interesting to note that the spectral distribution of these short pulses varies from pulse to pulse. In some cases the highest amplitude response occurs on the 1 MHz channel, while on other pulses the highest response occurs on the 10 MHz channel.

It is also evident from Figure 4-3 that a number of pulses occurred on the interior wire coincident with pulses on the antenna. Here again, there is no unique relationship between the amplitudes of the current spectral components. Furthermore, the amplitudes of the pulses occurring on the wire are not systematically related to the pulse amplitudes measured on the dipole antenna.

This apparent lack of relationship in the behavior of the various spectrum analyzer outputs can be rationalized as follows: Signals are induced in the inside wire primarily by currents flowing along the fuselage of the aircraft while currents along the wing will not induce appreciable signal in the wire. On the other hand, the field intensity at external dipole antenna location is relatively independent of the direction of current flow, (i.e., a given current along the wing produces relatively the same electric field as does the same current flowing along the fuselage). Thus, it is not unexpected that there is little apparent relationship between the amplitudes of the spectrum analyzer signals obtained from the two sensors.

More detail regarding the spectrum analyzer outputs is presented in Figure 4-4 which shows data obtained near the beginning of the flash (the region marked "Detail A" in Figure 4-3), and displayed at a sweep speed roughly 20 times faster than in the previous figure (Figure 4-3). Four pulses were induced in the external dipole antenna during the period of Figure 4-4. Although all four pulses were of roughly the same amplitude in the 1 MHz channel, the amplitudes of the pulses in the 3 and 10 MHz channels varied by more than a factor of two over the four pulses. In other words, the spectral character of the dipole antenna signal varied substantially from pulse to pulse.

Further inspection of Figure 4-4 indicates that only the last pulse produced appreciable reaction in the inside wire. It is interesting to note that the largest deviation from the zero line occurred on the 30 MHz channel and that barely perceptible deviations occurred on the 1 and 3 MHz channels.

It should be noted in Figure 4-4 that numerical values of spectral density are presented for the spectrum analyzer outputs. The calibration procedure employed is discussed in Appendix A. Basically, it consisted of applying to the antenna a train of pulses of known amplitude and fast rise time and recording the spectrum analyzer output. Since the antenna characteristics are known, it is possible to obtain a

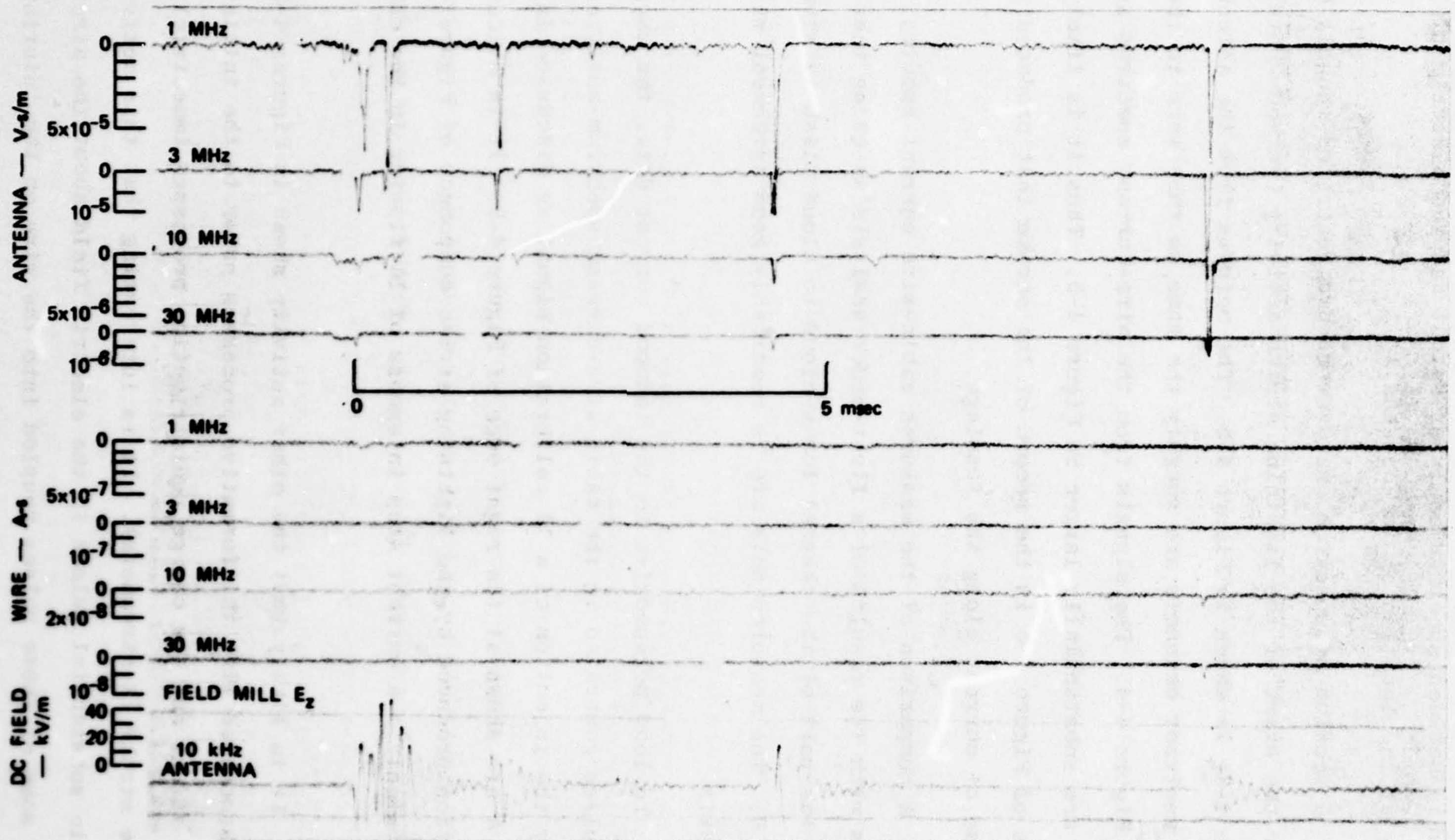

FIGURE 4-4 LIGHTNING STRIKE — DETAIL A

relationship between spectrum analyzer output and the electric field intensity at the location of the antenna.

A section of spectrum analyzer record generated roughly 0.05 sec after the start of the lightning strike activity (marked "Detail B" in Figure 4-3) is shown in Figure 4-5. The outputs from the antenna spectrum analyzer channels are roughly the same as they were in the last pulse of Figure 4-4. The signals from the wire-current spectrum analyzer, however, are substantially larger in Figure 4-5. Thus it is likely that the pulse of Figure 4-5 is the record of the stroke that produced the main pulse of current along the fuselage.

A comparison of the measured cabin-wire current spectral densities with the results of a first-order analysis assuming that the aircraft was part of the channel for a cloud-to-cloud flash is given in Appendix B. The measured data are in remarkably good agreement with the analysis.

To lend perspective to the induced current data, the magnitudes of the pulses generated in the cabin-wire-current spectrum-analyzer system by the injection of a 1A calibration signal as discussed in Appendix A are shown at the right edge of Figure 4-5. It is evident that the reaction produced by the lightning strike component of Figure 4-5 was equivalent to a current step in excess of 1A flowing in the cabin wire.

It is likely that the other activity shown in Figures 4-3 and 4-4 is associated with the formative processes prior to the initiation of the main stroke and the charge redistribution processes immediately after the stroke (K streamers). It is interesting that this activity results in substantial pulses in the electric field about the aircraft and that some of these pulses coupled into the wire on the interior of the fuselage.

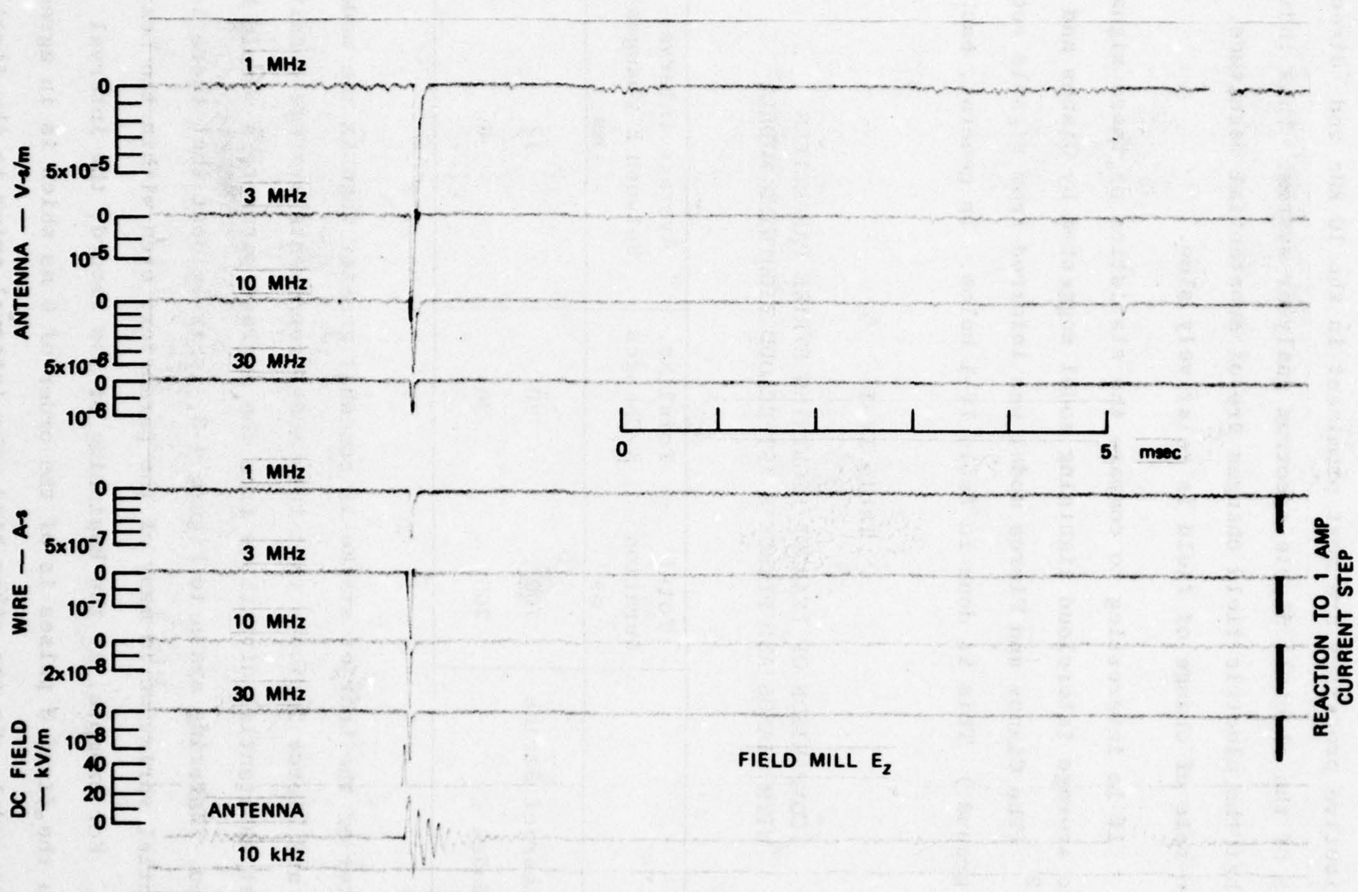

FIGURE 4-5 LIGHTNING STRIKE — DETAIL B

In general, the signals generated by K streamers or charge redistributive processes are most prominent in the 10 kHz and "direct" channels of the electric dipole spectrum analyzer system. This indicates that the electric field changes are of substantial magnitude, but that the rate of change of field is relatively slow.

It is interesting to compare the statistics of these signals with the average intercloud lightning model suggested by Cianos and Pierce.[2] (The Cianos and Pierce model was inferred from signals received on the ground.) This is done in Table IV-1 below. In general, each

Table IV-1

COMPARISON OF LEARJET LIGHTNING STRIKE PARAMETERS
WITH CIANOS AND PIERCE'S INTERCLOUD LIGHTNING MODEL

	Total Duration ms	Total No. K Changes	Average Interval Between K Changes ms
Learjet Strike	700	40	17
Model	200	30	6

parameter of the Learjet strike is somewhat greater than in the model. Cianos and Pierce indicate that this model represents average conditions, and that substantial diviations from the average parameters should be expected. Refering again to Figure 4-3, it is evident that there is substantial variation in many of the parameters even within the Learjet strike. For example, at the beginning of the record, the interval between the first 3 pulses is of the order of 6 ms which is in agreement with the model. On the other hand, the interval prior to the first pulse of detail B is roughly 25 ms.

2. Nearby Lightning

Interesting examples of nearby lightning are contained in the data from 10 August run 19 shown in Figure 4-6. This run was in heavy hail at an altitude of 37,000 ft under an anvil. Near the beginning of the record, two major pulses occur in the 10 kHz spectrum analyzer channel. The second of these is accompanied by pulses on all of the other spectrum analyzer channels, including those associated with the cabin wire. Associated with these pulses is a disturbance in the static field record, which indicates a field change of 15 kV/m as the result of the first lightning flash.

Near the end of the record of Figure 4-6, 8 major pulses occurred in the 10 kHz spectrum analyzer channel. Some of these were accompanied by signals in the remaining spectrum analyzer channels, including those measuring currents in the cabin wire. It should be noted that the magnitudes of the wire currents are comparable to those observed in detail A of the direct stroke (see Figure 4-4). At the conclusion of the electrical activity associated with the second flash, the static field was changed by 26 kV/m.

The portion of the first flash record of Figure 4-6 including cabin wire signals is shown in Figure 4-7 at about 500 times the sweep speed of the previous figure. It is evident that substantial signals were induced in the wire in the cabin--the largest was generated in the 10 MHz channel. (The apparent time difference between the various pulses in Figure 4-7 is an artifice of the tape recorder used and stems from the fact that the odd channels on the recorder feed one recording head, while the even channels feed another head which is displaced along the tape.) It is interesting to compare the amplitudes of the cabin wire sensor signals of the nearby lightning stroke of Figure 4-7 with those generated by the direct stroke to the Learjet. All of the current pulses

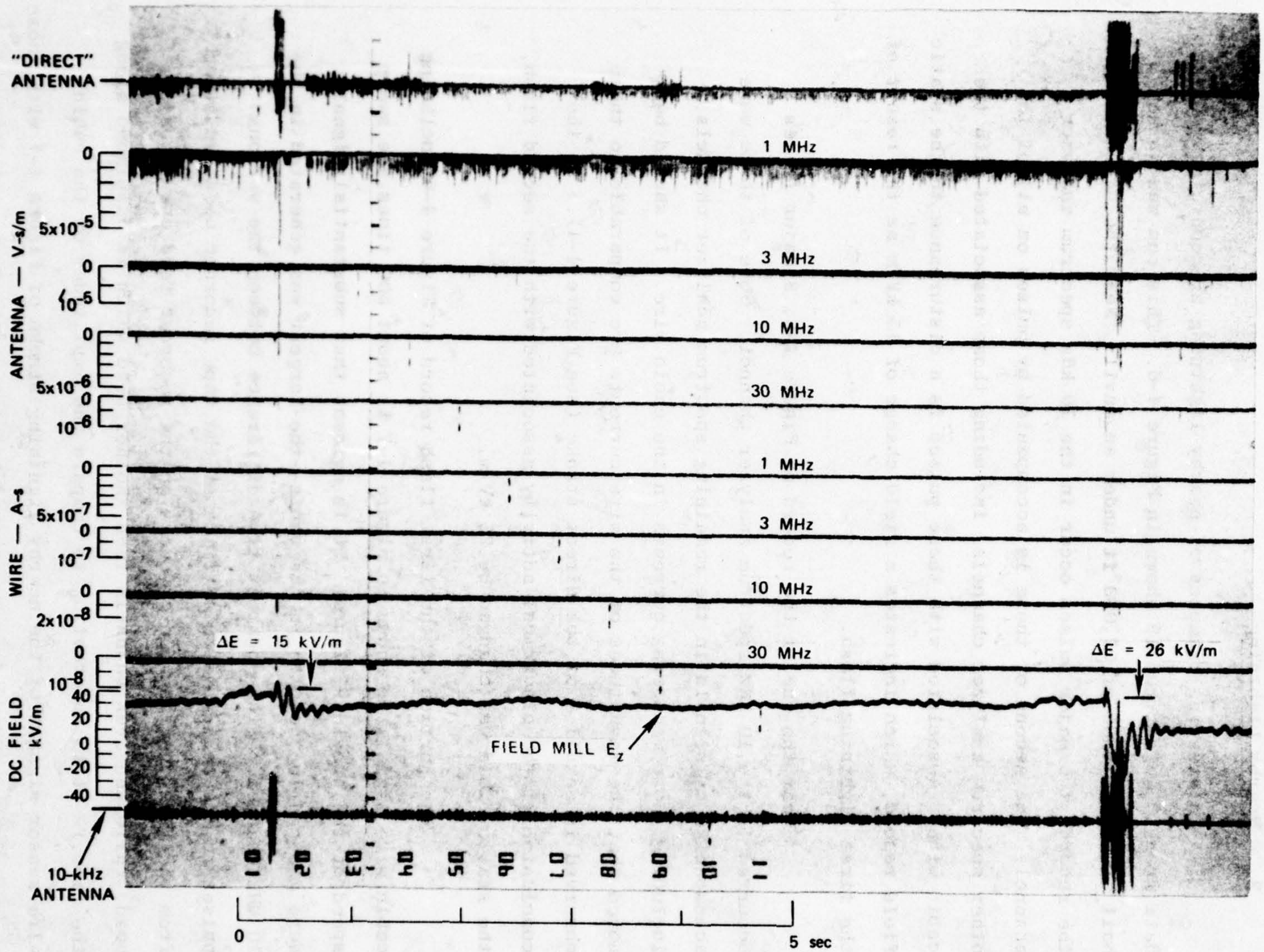

FIGURE 4-6 AUGUST 10 RUN 19 NEARBY LIGHTNING

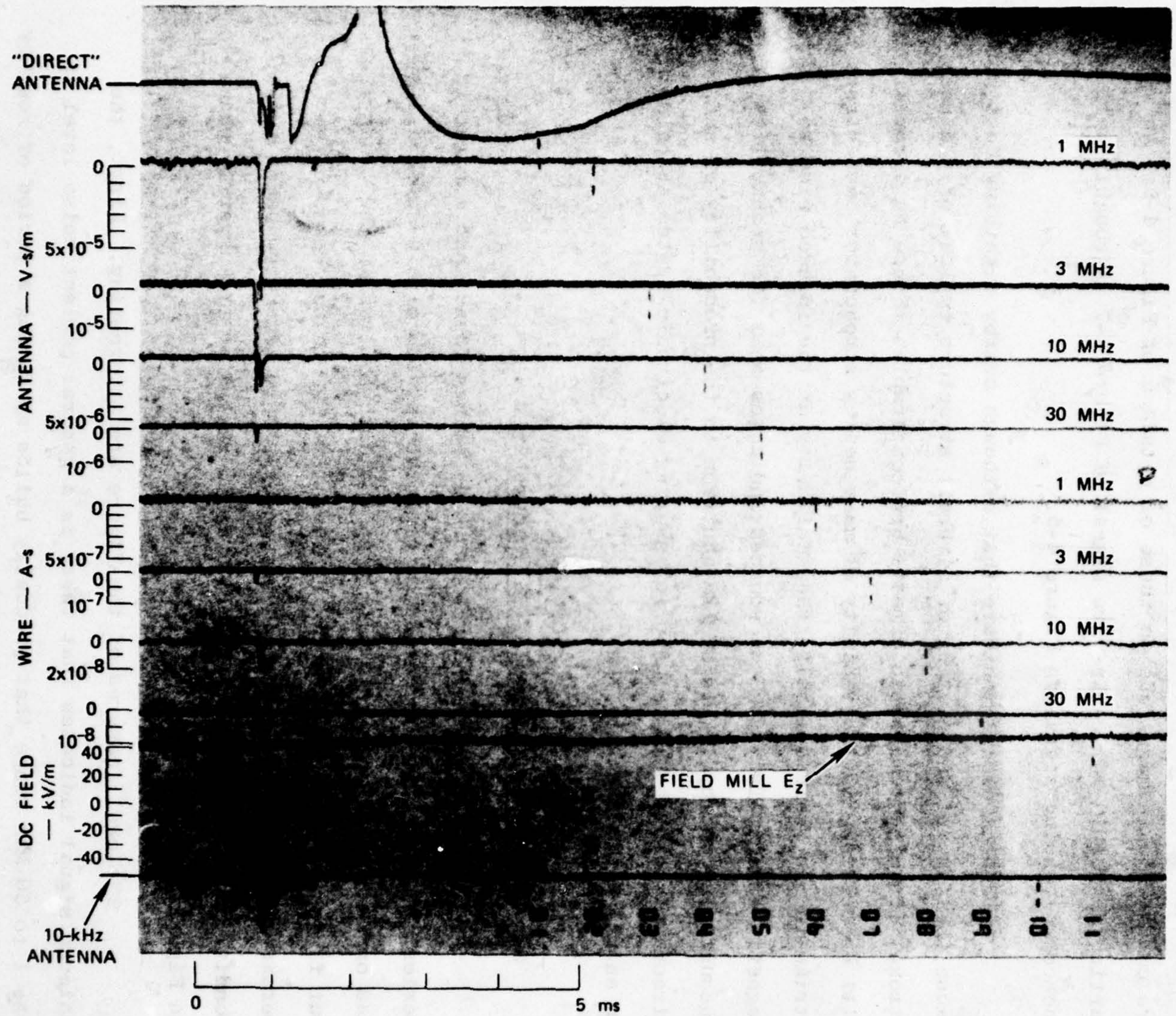

FIGURE 4-7 DETAIL OF FIRST LIGHTNING EVENT IN FIGURE 4-6

in Figure 4-7 are larger than the corresponding pulses of detail A in Figure 4-4. In fact, certain of the wire-current pulses of Figure 4-7 are comparable in magnitude to those of detail B of Figure 4-5. In particular the 10-MHz cabin-wire signal of Figure 4-7 is roughly half of the corresponding signal in Figure 4-5.

These results indicate that although nearby lightning does not cause the burning and pitting of aircraft structure typical of a direct stroke, its electromagnetic effects are comparable. Since an aircraft will normally be in the vicinity of many nearby strokes for each direct strike to the vehicle itself, the similarity of the induced electromagnetic effects from the two sources indicates that the probability of encountering nearby lightning (in addition to the probability of suffering direct strikes) should be used in assuring electronic system functioning in an all-weather environment.

3. "Incipient Lightning" Streamers

At times during the 1976 tests, it was found that a periodic series of noise pulses occurred on both the outside dipole antenna system and on the inside wire generally when the aircraft was in the clear air, but flying in the vicinity of a storm cell. The pulses would often persist for several minutes. A sample of record generated under such conditions at an altitude of 43,000 ft on run 28 of 11 August is shown in Figure 4-8.

Several features of the figure are interesting. First, the antenna signal indicates that there is a general ambient noise level in the 1 to 30 MHz range that gradually builds up during a period of roughly 2 sec until a major pulse occurs. At this time the 1 to 30 MHz noise level is reduced to zero for a period of roughly 0.3 to 0.5 sec. Then the noise in these channels again builds up until another major pulse occurs.

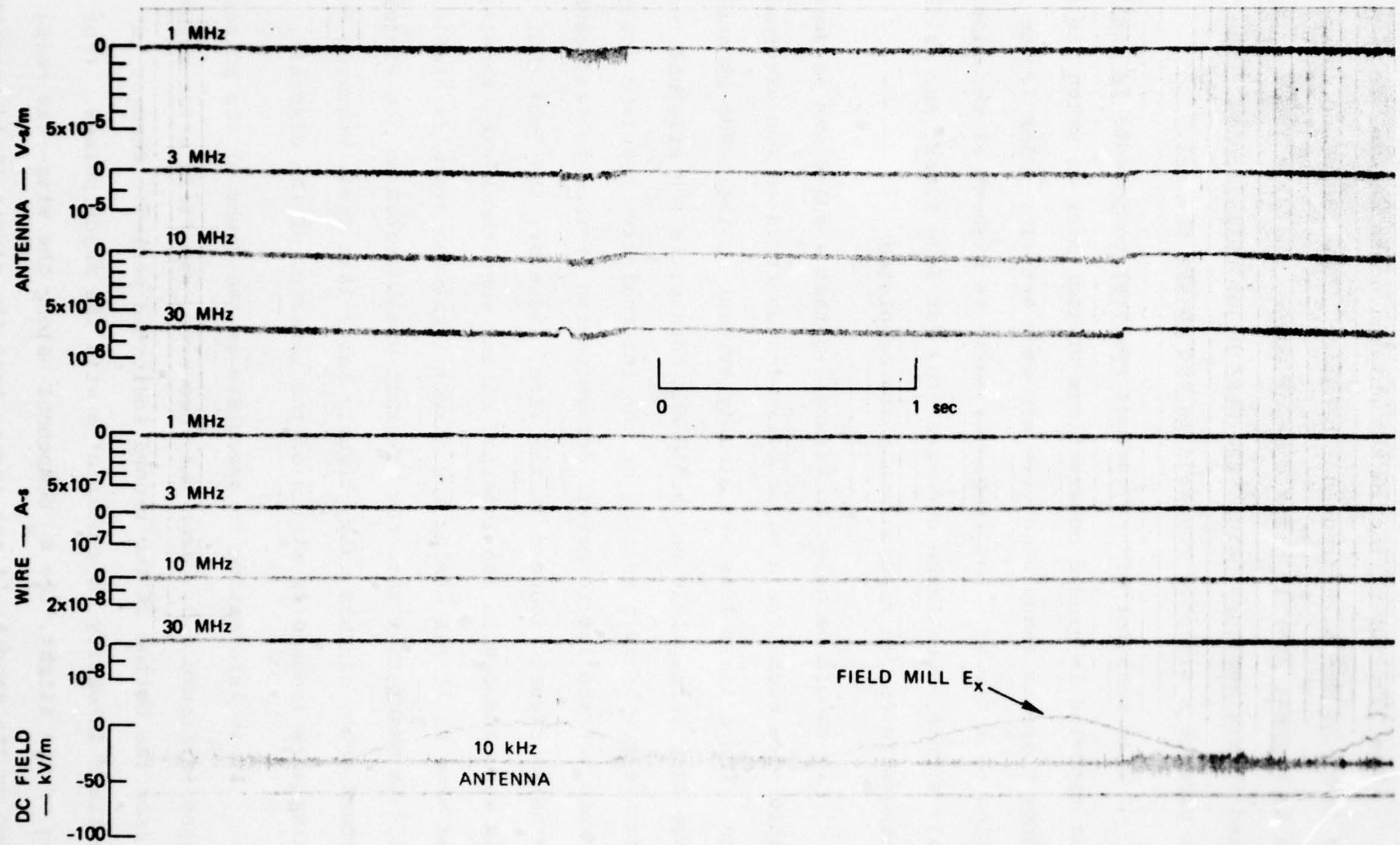

FIGURE 4-8 INCIPIENT LIGHTNING STREAMERS

The behavior of the 10 kHz antenna noise channel is roughly a mirror image of the high frequency behavior. The broadband noise at 10 kHz is highest shortly after a major pulse, and diminishes in magnitude and is minimum just before the next major pulse occurs. The major pulses produce a sizeable reaction in the 10 kHz channel.

This behavior of the various spectral components is similar to that reported in ground observations of lightning in which the high frequency noise is associated with streamer activity prior to the formation of a stroke. Low frequency noise is highest at the time of the main stroke, when large currents flow for long times, and falls off after the main charge readjustments are completed.

It should be noted in Figure 4-8 that a pulse was induced in the cabin wire each time a major pulse was observed on the external antenna. The noise pulses are clearly evident on the 1 MHz channel. They are also perceptible on the 10 MHz channel in the original records. Unfortunately, the gain setting on the internal-wire spectrum analyzer system was set too low to permit determination of the spectral character of the noise signals induced in the wire. However, the fact that signals were induced in the internal wiring when the system sensitivity was the same as it was during the direct lightning storm is highly significant. It means that when the aircraft was operated in the vicinity of a storm cell, signals only slightly lower than those produced by direct lightning were induced in wiring on the interior of the aircraft.

It is interesting to speculate on the cause of the pulses displayed in Figure 4-8. When they occurred, the field meter channel shown near the bottom of the record indicated periodic changes in static field intensity in synchronism with the major pulses. (For this portion of the flight, the E_x component--along the wing--was being recorded on the tape.) If one argues that the static field variations are the result of inhomogeneities in the electric field structure in the vicinity of the cloud, the time between peaks and the airplane speed ($\approx$ 250 m/s) means that the structure would have a spacing of roughly 500 m. For the pulses to persist for, say, a period of 20 sec, the region of inhomogeneous field would have to extend for a distance of 5 km. In addition, in order that the field variations from the inhomogeneities not become washed out, the distance from the aircraft to the source of the inhomogeneous charges would have to be comparable to the spacing between the inhomogeneities, or roughly 250 m.

An alternative explanation for the occurrence of the noise pulses and field indications of Figure 4-8 is that the aircraft was in a region of high electric field (50 to 60 kV/m in the record), and that streamers (that might have developed into triggered lightning, but didn't) were forming from an extremity on the aircraft. Conditions were not appropriate for one of the streamers to form a lightning stroke, but substantial charge transfer was involved in each streamer. Thus although the gross ambient field might be relatively uniform and steady, each streamer discharge would release substantial space charge in the vicinity of the aircraft and momentarily reduce the local field substantially, and quench off streamer formation. As the airplane flew along its track, it would fly out of the region of space charge into a clear region when the field would again be sufficiently high for streamer formation.

Unfortunately, the instrumentation system flown in 1976 did not allow determination of the source of the incipient lightning streamers. It is possible that they occurred from the wing. At the start of run 28 at an altitude of 43,000 ft, the observer indicated that a cell existed at 60° and 7 miles from the aircraft. If "incipient lightning" streamers were indeed occurring from a wing, they would excite transient currents along the wing with very little excitation of the fuselage. Thus one would expect very little coupling to the test wire inside the fuselage. Such streamers, on the other hand, would couple strongly to cabling within the wing. These arguments serve to reiterate the earlier observation that the observation of pulses on the internal test wire during periods of incipient lightning is highly significant.

A second example of "incipient lightning" taken from the data of 10 August run 2 at an altitude of 37,000 ft with the cell (top at 43,000 ft) 3 to 4 miles to the left of the aircraft, is shown in Figure 4-9. In this case, the repetition rate of the pulses is considerably higher (of the order of 10 pps), and the static field change associated with each breakdown is considerably less than in Figure 4-8. (It must be noted, however, that the E_x component--along the wing--was recorded in Figure 4-8.) In the record of Figure 4-9 again, a pulse was usually generated in the cabin wire each time a major pulse in the electric dipole occurred. As before, the cabin wire pulses are confined to two of the spectrum analyzer channels. They are quite prominent in the 1 MHz channel and barely perceptible on the original records in the 10 MHz channel.

Also of interest in Figure 4-9 is the way in which the noise spectra varied. Following a major pulse in the direct and 10 kHz channels, the broadband noise level in the remaining spectrum analyzer channels is markedly reduced. Also, it should be noted that, in the 10 kHz channel, each major pulse is followed by a burst of noise. It is also interesting that there are times when a reduction in noise level in the 1 to 30 MHz channels occurs, but is not accompanied by a major pulse in the direct and 10-kHz channels. In these cases there is no accompanying signal induced in the cabin wire.

These results indicate that a multiplicity of discharge processes may be active in the vicinity of a thunderstorm cell and that each generic

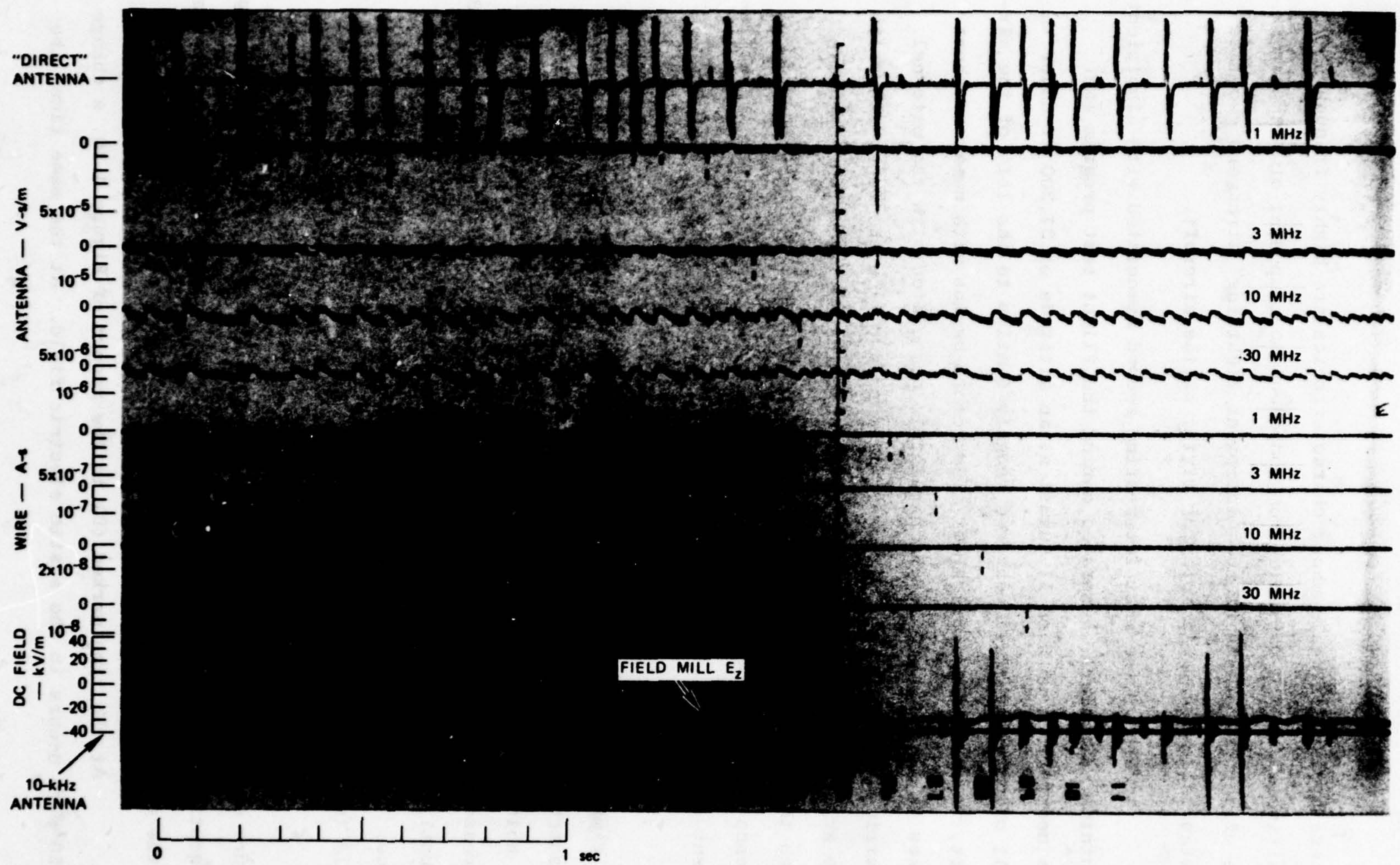

FIGURE 4-9 "INCIPIENT LIGHTNING" STREAMERS, AUGUST 10 RUN 2 process produces signals whose characteristics are highly frequency sensitive and quite variable from component to component of the process. Some of the components of the "incipient lightning" streamers generate substantial currents in interior wiring of the aircraft.

Perhaps the most interesting record associated with "incipient lightning" streamers, generated during the flight test program was obtained during run 9 on 11 August at an altitude of 37,300 ft under the anvil of an active cell centered roughly 4 miles to the left of the aircraft, is shown in Figure 4-10. The record begins with numerous short spikes on all spectrum analyzer channels associated with the external electric dipole antenna. At the time marked (A) on the record there is a 20 kV/m change in the static electric field followed by 3 pulses in which the noise levels on the 1- to 30-MHz channels of the dipole-antenna spectrum analyzer are reduced to zero. (These pulses are reminiscent of the "incipient lightning" streamers of Figures 4-8 to 4-9.)

The same pulse type occurs again starting about 4½ sec before the time marked (B) in the record. The time structure of these pulses is somewhat different from those shown in Figures 4-8 and 4-9, in that the noise in Figure 4-10 gradually decreases to zero and then abruptly increases to its maximum value, whereas the noise in Figures 4-8 and 4-9 abruptly decreases to zero and then gradually builds up to its maximum value. The pulses are synchronized with changes in the static electric field in this time interval.

The signals induced in the cabin wire by the streamers of Figure 4-10 are smaller than those shown in Figures 4-8 and 4-9. Barely perceptible pulses are generated in the 1-MHz channel, while the signals in the other channels are too small to be discerned.

At the time marked (B) in the record of Figure 4-10, a change of 50 kV/m occurs in the static electric field. At the same time, the

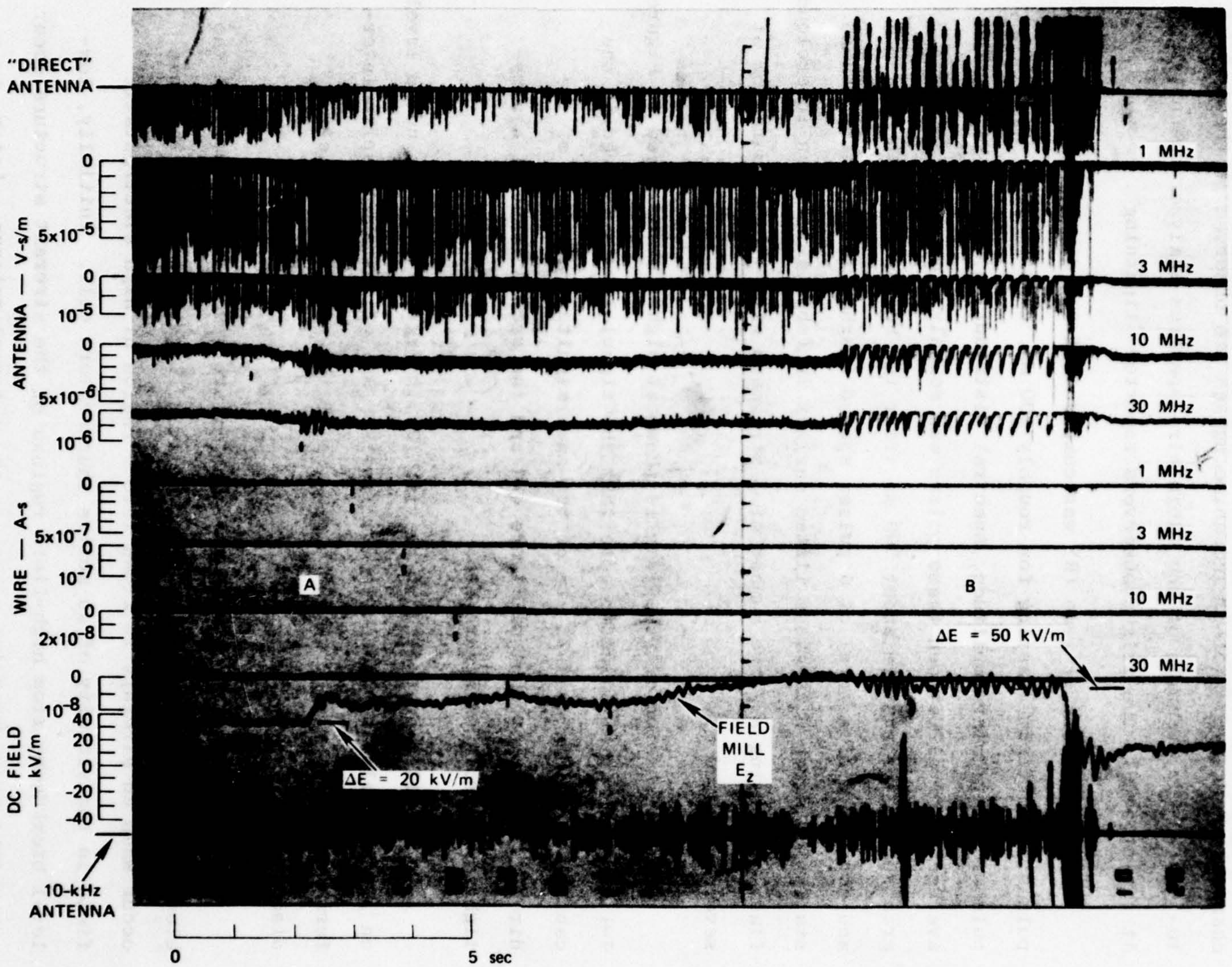

FIGURE 4-10 "INCIPIENT STREAMERS" FOLLOWED BY "LIGHTNING OBSERVED" nature of the signals in the electric-dipole-antenna spectrum-analyzer channels changes character, and noise pulses are observed in the 1-, 10- and 30-MHz channels of the cabin-wire spectrum-analyzer channels. At the time (B), the flight observers reported "lightning".

The flash at time (B) was composed of two distinct groups of pulses. The first, lasting for roughly 200 ms, consisted of about 44 pulses of irregular amplitude, spectral distribution, and spacing. The average interval between these pulses was roughly 5 ms. The second group of pulses started about 300 ms after the beginning of the flash and consisted of a total of 4 pulses spaced roughly 10 ms apart. These statistics agree with those listed earlier in Table 4-1 for an intercloud flash comprising a large number of K streamers with a total duration of several hundred ms.

A portion of the flash is shown at higher sweep speed in Figure 4-11. It is interesting to note that the signal levels induced in the cabin wire in Figure 4-11 are of the same magnitude as those of the direct strike component of Figure 4-4 and the second event of nearby-lightning-stroke of Figure 4-6.

Following the flash at time (B) in Figure 4-10, the noise level on all channels is reduced to low levels. All of the short-spike interference characteristic of the beginning of the record completely disappears.

Essentially, it appears that Figure 4-10 is the record of the electromagnetic processes short of a direct lightning strike that can occur when an aircraft is flown into a region of high electrostatic field in the vicinity of an active thunderstorm cell. Initially, low-level breakdowns from high-field regions of the aircraft structure occur generating numerous noise spikes in the external antenna. Later, as the static electric field intensity increases, incipient lightning streamers

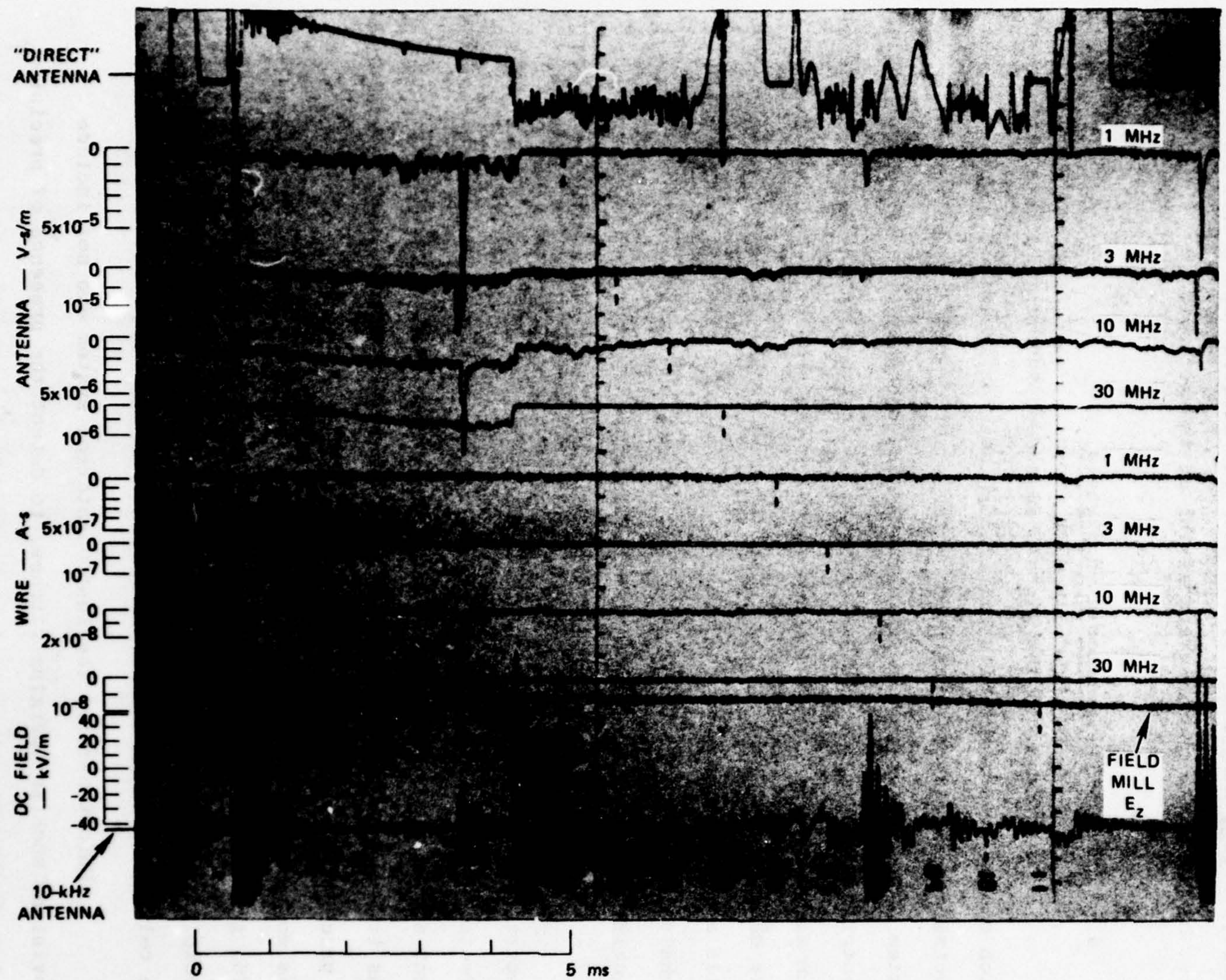

FIGURE 4-11 DETAIL OF LIGHTNING COMPONENT AT "B" IN FIGURE 4-10

begin to occur, and noise is coupled into the interior of the aircraft. Finally, a lightning flash occurs near the aircraft and generates a burst of pulses in the interior wiring of the aircraft.

4. Non-Lightning-Associated Signals

In addition to the signals discussed thus far in this section which can be associated with either lightning or incipient lightning, much electrical activity was observed on the external-dipole spectrum-analyzer system. Other signals were generated which probably were associated with electrification of the aircraft itself. When the aircraft was flown in clear air well away from thunderstorm cells and precipitation, no signals were observed on the antenna system. Within roughly 10 km of storm cells and when flying through the associated precipitation, noise pulse signals were observed on the external antenna but with no concomitant signals induced in the internal wire sensor.

When the system was being planned, it was recognized that an electric dipole is highly sensitive to aircraft charging and discharging effects. However, experience during 1975 was that most flight time was spent around clearly defined cells outside any region of precipitation. Thus it was felt that the brief periods when the aircraft was operated in precipitation would be sufficiently infrequent that the data from them would constitute a minor fraction of the total. As it developed in 1976, the study of anvil fields often brought the airplane into the precipitation either in the anvil itself or that blown off the top of the cell under study.

Unfortunately, the instrumentation system did not include provisions such as charging patches, to detect the presence of precipitation charging, so that it is not possible to segregate these data from those generated in clear air. (In flight, it is difficult to tell from visual observation whether the aircraft has indeed entered a region of cloud.) In addition, many of the good data runs when the various lightning events were observed occurred with the aircraft in precipitation. Accordingly, in reviewing the spectrum analyzer data from the flight tests, the procedure has been adopted of attributing to lightning effects only those events in which signals were obtained in both the external antenna and in the cabin wire sensor.

V COMPARISONS OF LEARJET LIGHTNING SPECTRAL DATA WITH OTHER INFORMATION

A. General

As a check on the validity of the 1976 lightning spectral measurements, it is instructive to compare the results with other data.

B. Spectral Amplitudes

It is interesting to compare the results obtained during the 1976 Learjet tests with current best estimates of spectral amplitudes of signals generated by nearby lightning flashes. E. T. Pierce has analyzed the results of ground measurements of lightning signals and has prepared curves indicating expected signal levels 300 m from a severe intracloud flash.[3] His results are shown in Fig. 5-1. Also shown in the figure are data obtained with the Learjet spectrum analyzer system in the vicinity of nearby lightning flashes. It is apparent that the 1976 Learjet data correspond quite well to the predicted levels.

Although lightning is a more frequent hazard to aircraft, much effort has been spent on nuclear EMP. Thus it is instructive to compare the characteristics of the two sources. Accordingly, curves showing the spectra of the various nuclear EMP pulse models of Ref. 4 are also shown in Fig. 5-1. (The corresponding EMP time waveforms are shown in Fig. 5-2.) It is evident from Fig. 5-1 that, at low frequencies, nearby lightning constitutes a far more energetic threat than does EMP. Even at frequencies of 10 mHz and above, nearby lightning cannot be completely ignored in comparison to EMP.

C. Waveforms Observed with Transient Digitizer

As noted earlier in Section II-C, the Learjet was also instrumented with a transient digitizer system[5] to record the transient signals generated in the external electric dipole antenna and in the wire sensor

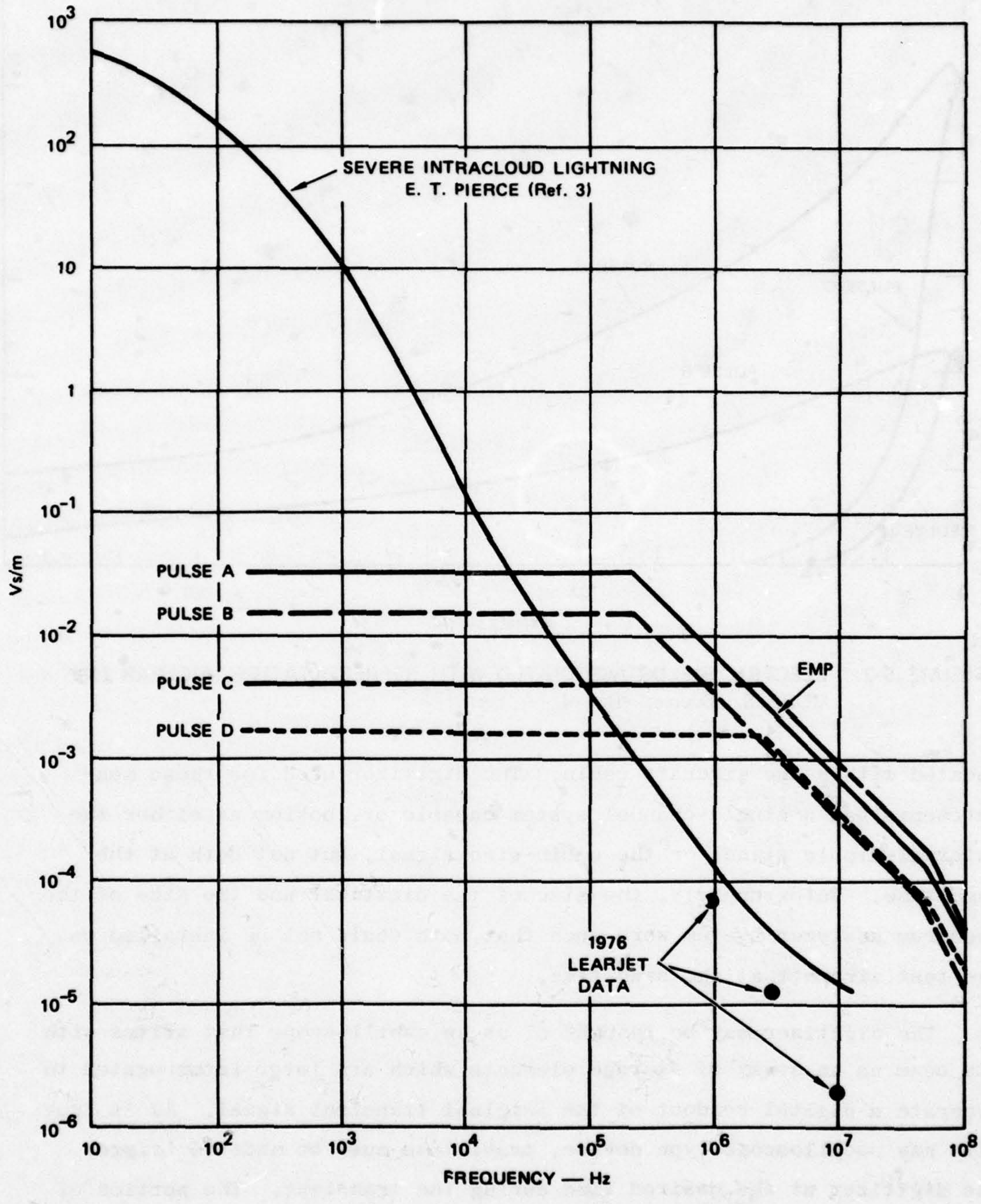

FIGURE 5-1 SIGNAL SPECTRAL DENSITIES

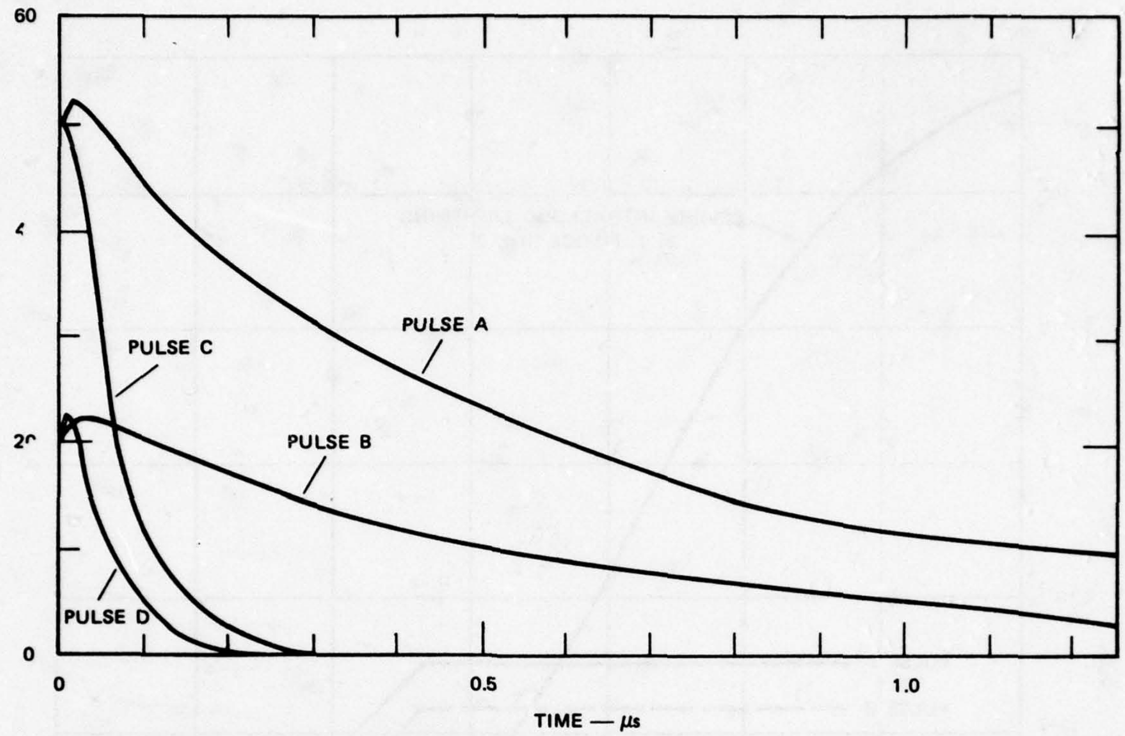

FIGURE 5-2 ELECTRIC FIELDS ASSOCIATED WITH REPRESENTATIVE NUCLEAR EMP MODELS. Source: Ref. 4.

located within the aircraft cabin. The digitizer used for these measurements was a single-channel system capable of looking at either the external-dipole signal or the cabin-wire signal, but not both at the same time. Unfortunately, the size of the digitizer and the size of the spectrum analyzer system were such that both could not be installed on the test aircraft at the same time.

The digitizer may be thought of as an oscilloscope that writes with its beam on an array of storage elements which are later interrogated to generate a digital readout of the original transient signal. As is true with any oscilloscope-type device, provisions must be made to trigger the digitizer at the desired time during the transient. The portion of the transient recorded depends on the triggering time and on the sweep speed established for the measurement. Once the digitizer is fired and records a signal, there is an inevitable delay before another transient can be observed. Thus, the digitizer presents single, high-resolution snapshots of the events occurring at the general time of the triggering event.

A variety of transient signals were recorded during the time that the digitizer was flown. It was found that no signals were observed when the aircraft was well away from storm cells. In the vicinity of the cell or when flying through portions of the anvil, various pulses were observed.

A sample of a typical record type is shown in Fig. 5-3. The triggering was such that the rise of the signal is not displayed. The

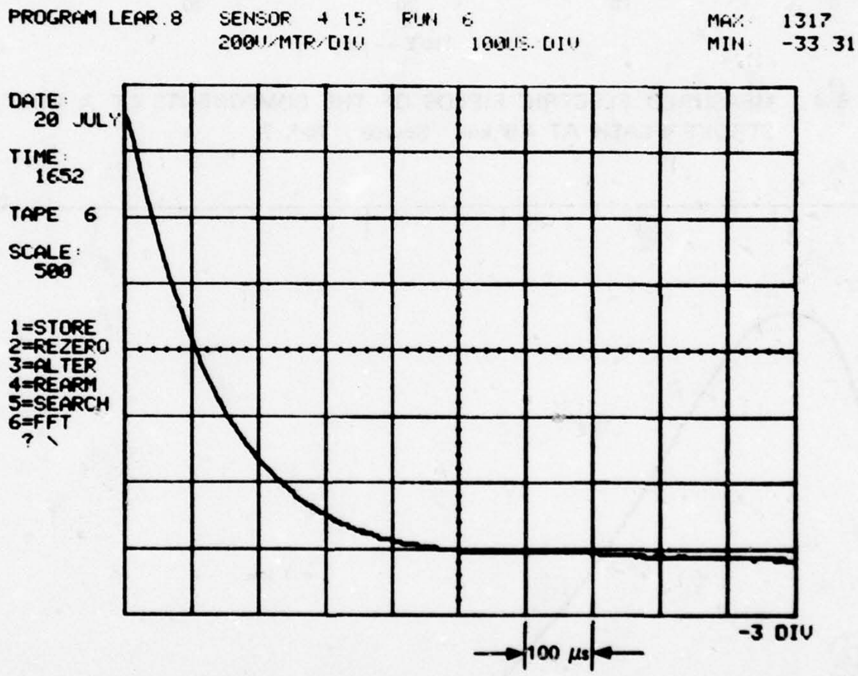

FIGURE 5-3 TRANSIENT DIGITIZER RECORD OF LIGHTNING SIGNAL

entire decay period, however, is shown on the record. It is very likely that Fig. 5-3 represents the signal generated by one component of a nearby lightning flash. For comparison, two measured pulses generated in a multiple-stroke cloud-to-ground flash are shown in Fig. 5-4.[7] Also for comparison, a predicted E-field pulse from a K streamer is shown in Fig. 5-5.[8] The decay of Fig. 5-3 is of the right form, but somewhat

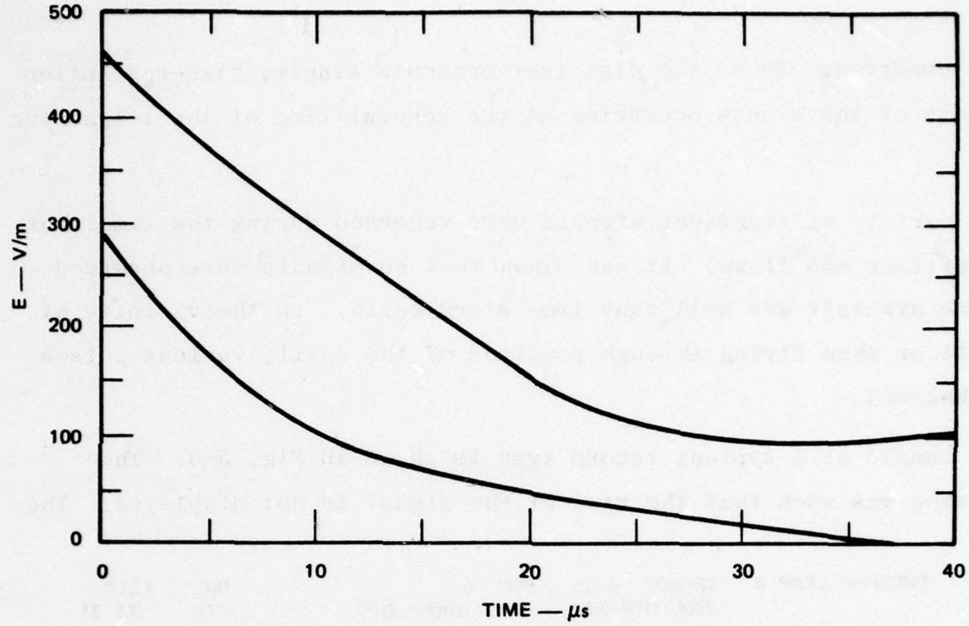

FIGURE 5-4 MEASURED ELECTRIC FIELDS OF THE COMPONENTS OF A MULTIPLE-STROKE FLASH AT 4.5 km. Source: Ref. 7.

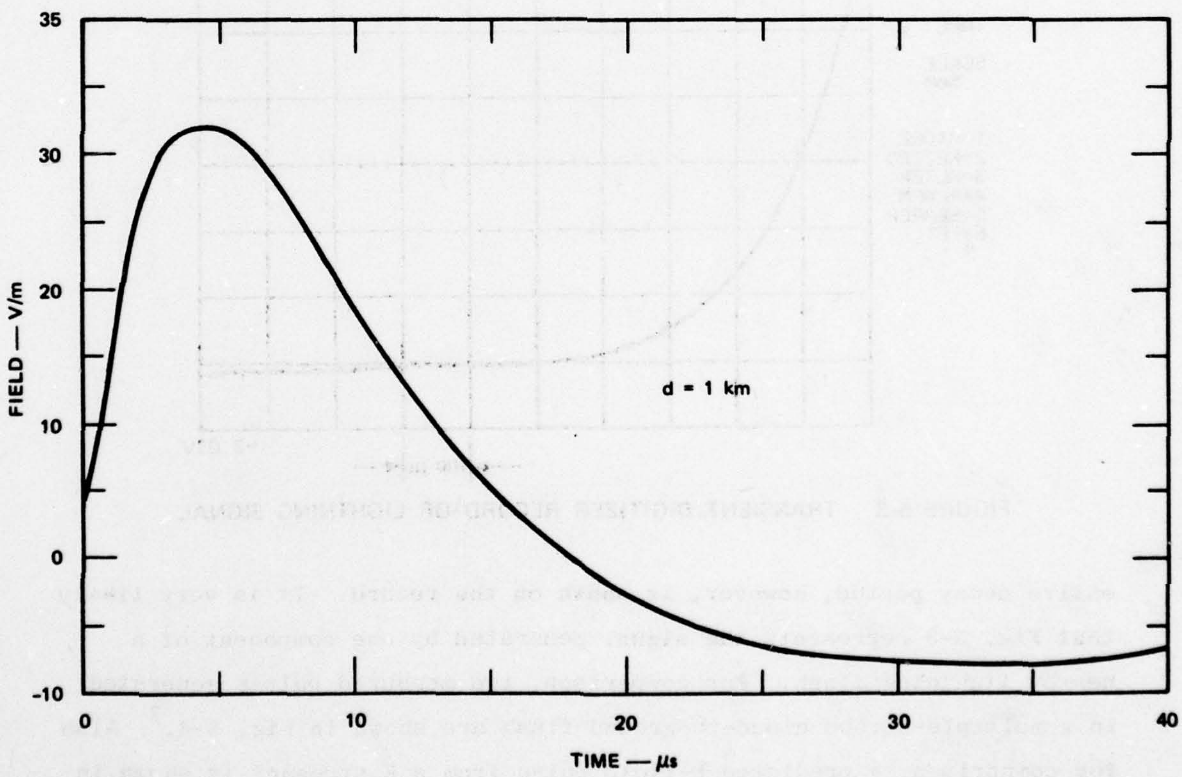

FIGURE 5-5 PREDICTED ELECTRIC FIELDS FROM LIGHTNING K PULSES. Source: Ref. 8.

longer than either of the comparison pulses. The amplitude is in the same range as the cloud-to-ground flash of Fig. 5-4.

As noted above, the 1976 Learjet instrumentation system did not permit simultaneous recording of digitizer and spectrum analyzer data. Thus it is not possible to put the record of Fig. 5-3 into context regarding its position in a flash--e.g., is it one of the field charges associated with the formation of the flash, or is it representative of one of the main, high-current components of the flash.

Another record typical of the time structure associated with lightning-generated signals is shown in Fig. 5-6. The sweep speed here

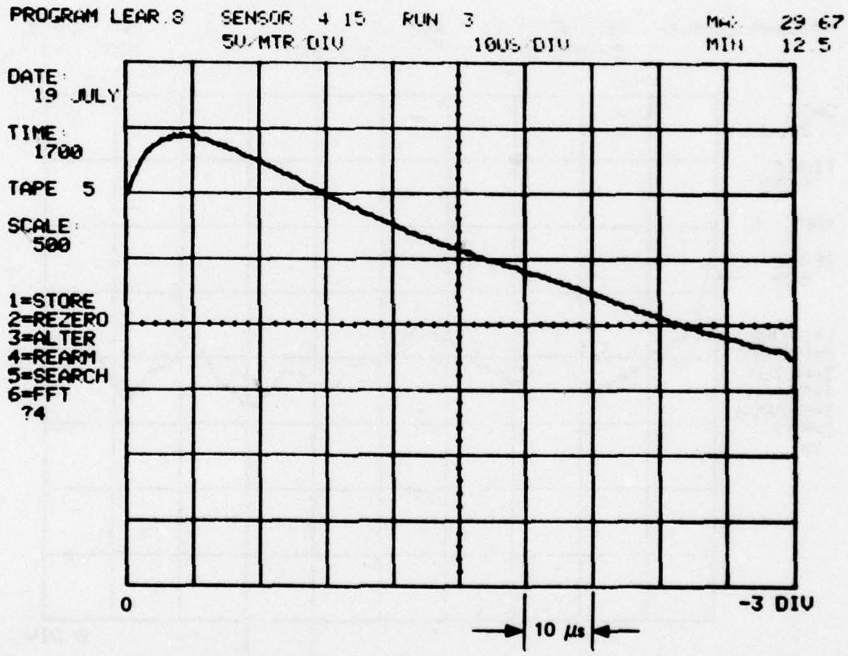

FIGURE 5-6 TRANSIENT DIGITIZER RECORD OF LOWER-LEVEL SIGNAL TYPICAL OF LIGHTNING

is a factor of 10 higher than it was in Fig. 5-3. Triggering in Fig. 5-6 is such that a portion of the signal rise is recorded. The peak amplitude of the field in Fig. 5-6 is a factor of roughly 50 lower than in Fig. 5-3 indicating that either its source was farther from the aircraft or that the pulse was generated by a K streamer which produce lower amplitude signals as is shown in Fig. 5-5. Again, there is no continuous record available to put the record of Fig. 5-6 into context regarding its position in the lightning flash with which it is associated.

A third record generated by the transient digitizer is shown in Fig. 5-7. It should be noted that the sweep speed on this record is very slow--1 ms/div. The slow, random field variations are typical of the aircraft potential fluctuations that one might associate with flight through a high-altitude cloud capable of producing aircraft charging by triboelectric processes. Similar noise-like records were obtained with the spectrum analyzer system when the aircraft was operated in high-altitude precipitation.

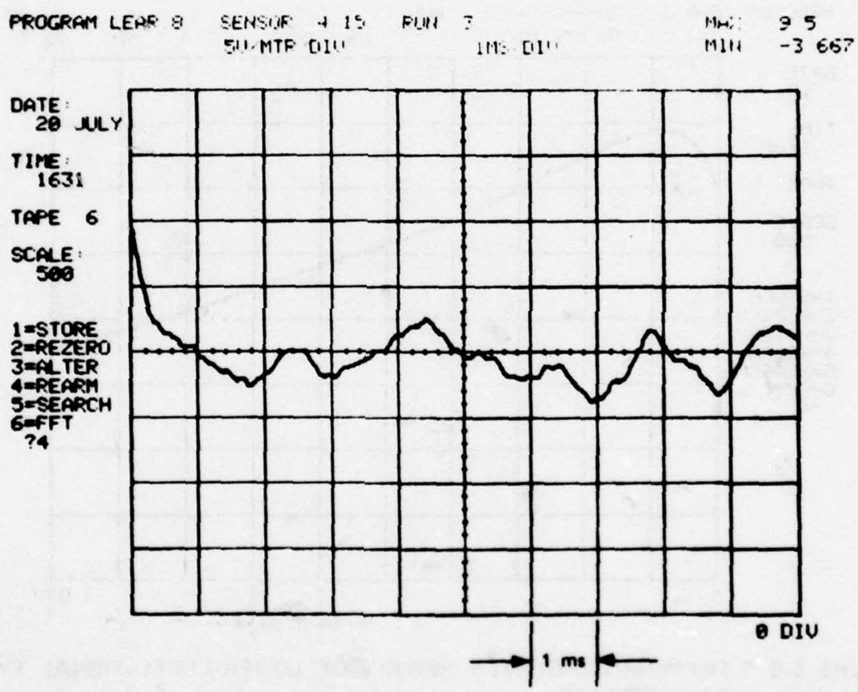

FIGURE 5-7 TRANSIENT DIGITIZER RECORD GENERATED BY NON-LIGHTNING PROCESSES

VI CONCLUSIONS AND RECOMMENDATIONS

In conclusion, it may be stated that the quick-reaction flight-test program to investigate the transients associated with nearby lightning was highly successful. Two instrumentation systems--a transient digitizer and a discrete-frequency spectrum analyzer--were flown on a Learjet aircraft in the vicinity of active Florida thunderstorm cells. Measurements were made of the signals induced in an external electric dipole antenna located on the top of the fuselage and in a special wire sensor located on the inside of the cabin.

Measured spectral intensity data associated with nearby lightning are in good agreement with predicted values published by E. T. Pierce. A comparison of signals induced in the cabin wire by nearby lightning with signals generated by a direct stroke to the aircraft indicated the the nearby lightning was almost as serious (within a factor of two) a source of interference as the direct stroke.

Signals generated when the aircraft was flown in a region of high electric field near an active thunderstorm cell often generated electromagnetic pulses which persisted for periods of minutes. It was found that this activity, tentatively identified as "incipient lightning streamers," also generated pulses in the internal wire. This mechanism should be studied further in succeeding flight tests.

The tests also served to illustrate improvements in the instrumentation system that would permit additional important questions regarding both the noise sources associated with thunderstorm cells and the signals induced in aircraft systems to be answered. First, the nature of a typical lightning flash is such that many high-speed events occur over a substantial time period. The continuous spectrum analyzer record should be used to provide the continuity that puts the transient digitizer records into the proper perspective regarding where in the overall flash the digitizer record was made. In other words, the digitizer and spectrum analyzer should be operated together on each flight. To further put the measurements in perspective, provisions should be made to record the static electric field about the aircraft.

The signals generated by an electric dipole are complicated by the fact that such an antenna responds strongly to charging processes associated with the aircraft itself. Accordingly, provisions should be made to measure the "free-space" fields generated by the thunderstorm sources using an antenna highly decoupled from the airframe (for example, a loop on an extremity such as the nose).

Since the signals coupled into the interior of an aircraft are related to the current flowing on the member containing the wire in question, provisions should be made to measure gross skin current on two orthogonal members of the aircraft (such as the fuselage and a wing).

A preliminary estimate of the current induced in the cabin wire by signals coupled through the windows indicates that this mechanism is capable of accounting for the measured currents. The calculations together with the experimental data demonstrate the importance of accurate information regarding the leading edges of the driving pulses. The results also suggest that there is much variation in the high-frequency characteristics of successive components of a flash since some induce currents in the cabin wire and others do not.

Appendix A

ELECTROMAGNETIC SENSOR DESIGN AND CALIBRATION

Appendix A

ELECTROMAGNETIC SENSOR DESIGN AND CALIBRATION

1. Electric Dipole Characteristics

In planning the exterior electromagnetic field sensor for the aircraft, various considerations were important. First, it was essential that the sensor be simple in order that it be possible to carry out design, fabrication, and installation in a matter of a week. Second, it was necessary that the design be such that its installation not compromise safety of flight. Since the aircraft already included provisions for installing a wire antenna between a feed-through insulator on the top of the fuselage and a point on the top of the fin, it was decided that the sensor be a short electric dipole mounted on the normal antenna insulator.

In measuring transient electromagnetic signals, it is necessary that the receiving antenna be either very long and resistively loaded or that it be short compared to the highest wavelength of interest. With a short antenna, the ringing introduced by reflections from the ends of the antenna is designed to be beyond the pass band of the measuring system so that it does not show up in the measurements. The 24-inch-long wire used for the 1976 tests was chosen as being sufficiently short for the intended measurements.

A short dipole antenna has the equivalent circuit shown in Fig. A-1.[6] For a highly-top-loaded dipole, the effective height h_e is equal to the physical height of the antenna. For antennas with other physical forms, both h_e and antenna capacitance C_A generally must be determined by measurement. The values of the parameters of the Learjet antenna were determined from the experimental data of Reference 6.

Given the electrically short antenna of Fig. A-1, it is next necessary to decide upon its termination. If the antenna is capacitively

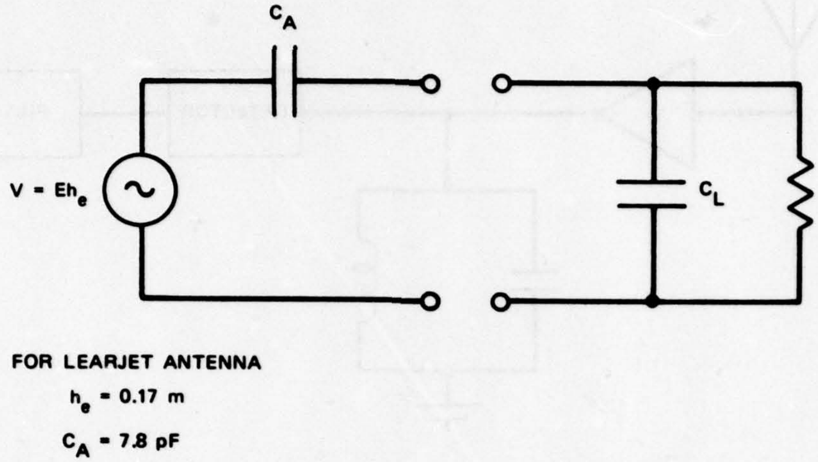

FIGURE A-1 EQUIVALENT CIRCUIT OF SHORT ELECTRIC DIPOLE

terminated, then the terminal voltage is directly proportional to the ambient field E:

$$V_{out} = k\, h_e\, E\,(t).$$

(With a resistive termination, the output voltage will be proportional to the derivative of the field.)

For the flight tests the parameters of the input circuitry were chosen so that $R_L >> \frac{1}{\omega C_L}$ down to the lowest frequencies of importance so that signals directly proportional to the ambient electric field at the antenna location were applied to the input of the transient digitizer and spectrum analyzer.

2. Spectrum Analyzer Calibration

The functional circuit of the spectrum analyzer used in the 1976 Learjet tests is shown in Fig. A-2 together with an indication of the

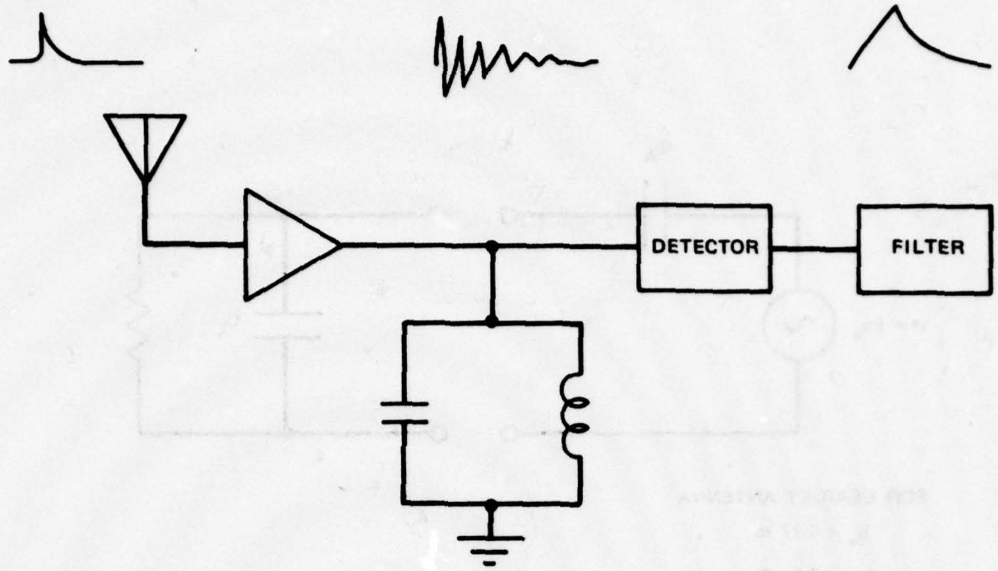

FIGURE A-2 FUNCTIONAL DIAGRAM OF SPECTRUM ANALYZER

waveforms expected at various points in the system in response to an input transient signal. An input signal pulse excites the tuned circuit and causes it to generate the indicated damped oscillation the magnitude of which is proportional to the energy in the original pulse contained within the pass band of the tuned circuit. The damped oscillatory signal is rectified and smoothed to generate the indicated output pulse whose length is determined by tuned circuit and output filter characteristics, and whose amplitude is proportional to the amplitude of the input signal.

In-flight calibration of the spectrum analyzer was accomplished by applying a train of pulses of terminal through a 3.3-pF capacitor as shown in Fig. A-3, and recording the resulting output pulses on the analog tape recorder. (The pulse rise time and durations were chosen so that the pulse had a clearly-defined transform over the frequency range of the spectrum analyzer.) From the equivalent circuits shown, it is possible to establish an equivalence between the calibration voltage and electric field required to produce the same input to the spectrum analyzer system as follows:

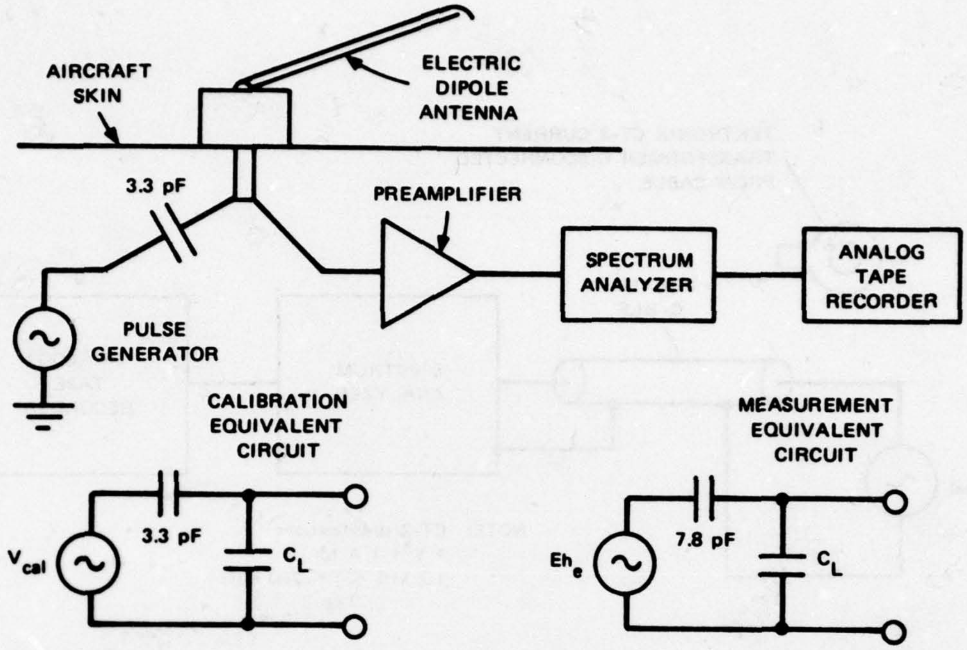

FIGURE A-3 IN-FLIGHT CALIBRATION OF ELECTRIC-DIPOLE SPECTRUM ANALYZER SYSTEM

$$V_{cal} \frac{3.3}{3.3 + C_L} = Eh_e \frac{7.8}{7.8 + C_L}$$

which, upon rewriting, becomes

$$E = \frac{3.3}{7.8} \frac{V_{cal}}{h_e} .$$

In-flight calibration of the cabin-wire spectrum analyzer system was accomplished as indicated in Fig. A-4 by disconnecting the current transformer from the spectrum analyzer input and replacing it with the calibration pulse generator. From the transformer specifications, it is possible to establish a relationship between the calibration pulse voltage and cabin-wire signal current. (i.e., a 1 volt calibration pulse is equivalent to a 1 amp wire signal pulse.)

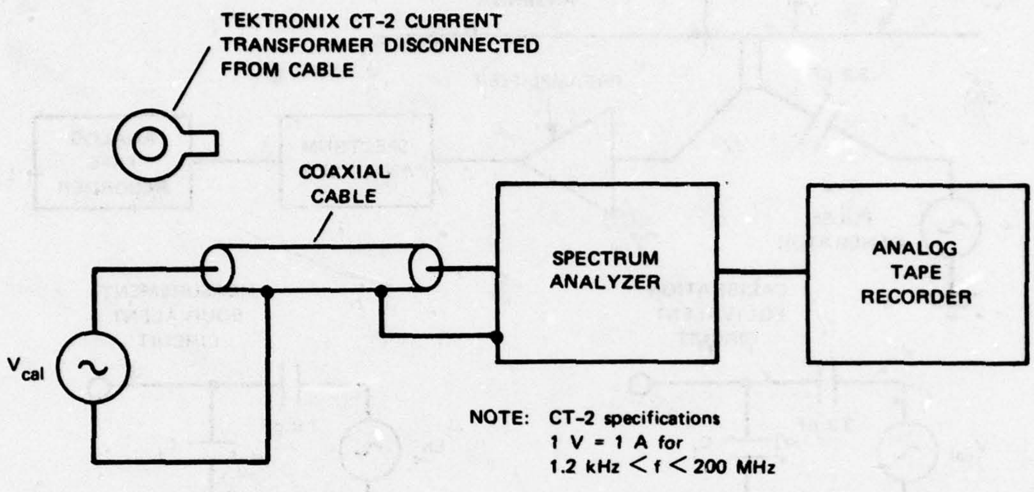

FIGURE A-4 IN-FLIGHT CALIBRATION OF CABIN-WIRE SPECTRUM ANALYZER SYSTEM

To derive the numerical calibrations as shown on the flight test records starting with Fig. 4-3, the spectral density of the calibration signal was established for each spectrum analyzer frequency by Fourier transforming the calibration pulse. The peak of the calibration signal as recorded on the analog tape recorder was labelled with this value of spectral density (or equivalent field spectral density). A similar procedure was followed to derive the noise current spectral density for the cabin-wire-current spectrum analyzer channels.

The pulses shown on the right margin of Fig. 4-5 are simply the amplitudes of the output pulses produced by a 1 volt calibrating step applied as shown in Fig. A-4.

Appendix B

ANALYSIS OF LIGHTNING CURRENT COUPLING TO LEARJET CABIN WIRE ANTENNA

Appendix B

ANALYSIS OF LIGHTNING CURRENT COUPLING TO LEARJET CABIN WIRE ANTENNA

1. Diffusion of Signals Through Skin

An analysis was made to determine the signal levels that would be generated in the cabin-wire antenna by diffusion of fields through the aircraft skin, which would then couple to the interior test antenna. The hypothesis was tested using a simple cylindrical model of the aircraft driven by a 10 kA peak stroke with the current flowing along the fuselage. The predicted noise-current spectral densities resulting from this coupling mechanism are orders of magnitude below the measured values. Thus it was concluded that field diffusion through the skin was not the mechanism responsible for coupling into the interior of the aircraft.

Other mechanisms capable of coupling lightning signals into the interior of the aircraft are aperture coupling and hard wire connections to the interior of the aircraft from a region such as the radome. Only the aperture coupling mechanism was examined here.

2. Aperture Coupling of Signals to Internal Wire

a. Leakage Inductance, Wire Current

Let us postulate that the internal wire loop is excited by magnetic field leakage through the cabin windows in the Learjet. The voltage induced in the loop will be

$$v = M \, di/dt$$

where i is the fuselage current and M is the leakage inductance of the windows. For one circular window,

$$M_1 = \frac{\mu_o \vec{M}}{4\pi^2 a^2} = \frac{10^{-7}}{\pi a^2} \vec{M}$$

where $\vec{M} = 4 r_o^3/3$ is the polarizability of the window and r_o is the radius of the window. For a 1 ft. diameter window, $r_o = 0.15$ m and $\vec{M} \approx 4.5 \times 10^{-3}$ m^3. The leakage inductance for each window is then $M_1 \approx 2.46 \times 10^{-10}$ H.

The loop current will be

$$i_w = \frac{1}{L} \int vdt = \frac{M}{L} i$$

where L is the loop inductance. The loop inductance is

$$L = \frac{\ell Z_o}{c} = \frac{3}{3 \times 10^8} Z_o$$

since ℓ = wire length $\approx$ 3 m, and c = speed of light.

Z_o is given by $Z_o = 60 \ln \frac{2h}{a} = 60 \ln \frac{10}{.016} = 383$

since h = 5", a = 16 mil, (#20 gage wire).

Thus the inductance is $L = 3.83 \times 10^{-6}$ Henries.

The wire current is then

$$i_w \approx \frac{M}{L} i = \frac{2.46 \times 10^{-10}}{3.83 \times 10^{-6}} ni = 6.44 \times 10^{-5} ni$$

where n is the number of windows. For 10 equal-size windows (say that the 4 assorted windows in the fuselage are equivalent to 6 one-foot-diameter windows and that the 2 cockpit windows are equivalent to 4 one-foot-diameter windows), we obtain for the relationship between wire current and fuselage current:

$$i_w = 6.44 \times 10^{-4}\ i$$

in either the time or frequency domain.

b. Some Other Considerations

The wire resistance is about .09 Ω ; therefore, the wire loop looks inductive for

$$\tau \le \frac{L}{R} = \frac{3.83 \times 10^{-6}}{.09} \approx 42\ \mu s$$

$$f >> \frac{R}{2\pi L} = \frac{.09}{2\pi \times 3.83 \times 10^{-6}} = 3.8\ \text{kHz}$$

and the inductance dominates in the 1-30 MHz range.

If the riveted joints in the skin have enough resistance, the transfer impedance will be R + jωM instead of jωM. Assuming a joint resistance of about 1 m Ω , the jωM term will be dominant for

$$f >> \frac{R}{2\pi M} \approx \frac{10^{-3}}{2\pi\ 2.46 \times 10^{-9}} = 65\ \text{kHz}$$

and the leakage inductance dominates in the 1-30 MHz range.

c. Source Spectrum

Cianos and Pierce,[2] using indirect data, have deduced that the K-change waveform is given by

$$i(t) = I\left[(e^{-at} - e^{-bt}) + 1/3\ (e^{-ct} - e^{-dt})\right]$$

where I = 19.3 kA

and $a = 5 \times 10^4$ $b = 2 \times 10^5$

$c = 5 \times 10^3$ $d = 2 \times 10^4$

The Fourier transform of the waveform is

$$I(\omega) = I\left[\frac{1}{j\omega + a} - \frac{1}{j\omega + b} + 1/3\left(\frac{1}{j\omega + c} - \frac{1}{j\omega + d}\right)\right]$$

$$\approx I\left[\frac{b - a}{(j\omega)^2} + 1/3\,\frac{d - c}{(j\omega)^2}\right] \quad (j\omega >> a, b, c, d)$$

$$\text{or} \quad \left|I(\omega)\right| \approx \frac{I}{\omega^2}\left[15 \times 10^4 + 5 \times 10^3\right] = \frac{I}{\omega^2}\, 15.5 \times 10^4$$

The corner frequencies for ω = a, b, c, d are

$$f_a = \frac{5 \times 10^4}{2\pi} = 7.9 \text{ kHz}$$

$$f_b = 32 \text{ kHz}$$

$$f_c = 0.79 \text{ kHz}$$

$$f_d = 3.2 \text{ kHz}$$

So for 1-30 MHz, the $1/\omega^2$ variation applies and

$$I(\omega) = \frac{19.3 \times 10^3 \times 15.5 \times 10^4}{\omega^2} = \frac{3.03 \times 10^9}{\omega^2} \text{ (for a 10 kA peak pulse).}$$

This current spectrum is shown in Figure B-1 as the line marked "Cianos and Pierce Source." Also shown in this figure are the measured wire current data from the 10 August lightning strike component shown in Figure 4-5. It is evident from Figure B-1 that the measured noise level was substantially higher and that the measured spectrum did not fall off as rapidly with increasing frequency as did the calculated spectrum.

Since the form of the wire current spectrum duplicates the form of the skin current spectrum, it was felt that some experimentation with the k-streamer source would be instructive. Accordingly, the

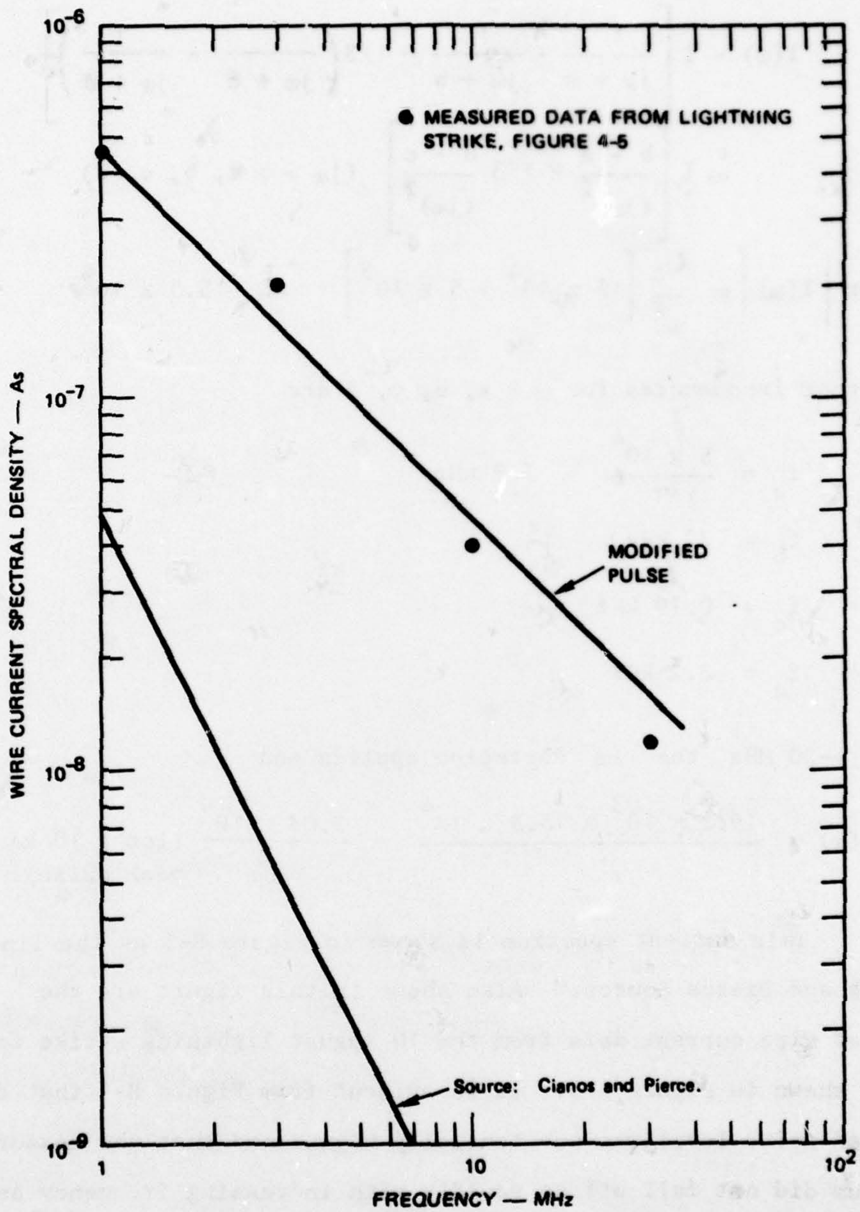

FIGURE B-1 COMPARISON OF CALCULATED WIRE-CURRENT SPECTRA WITH MEASURED DATA

Cianos and Pierce waveform was modified by permitting $d' \rightarrow \infty$ and by changing the constant I to $I = 1.29 \times 10^4$ A. These two changes have the effect of keeping the peak pulse current the same, but of decreasing the rise time of the second (smaller) component of the model pulse--i.e., letting it go to zero. The two waveforms are shown in Figure B-2 for comparison. On a linear-time-scale plot of this sort, the difference between the two pulse forms appears minimal.

The decrease in rise time has the effect of making the

$$\frac{1}{j\omega + c}$$

term in the Fourier transform dominate in the frequency range of interest. Thus the magnitude of the spectral density will be increased in the measured frequency range, and it will have a $1/\omega$ dependence instead of a $1/\omega^2$ dependence on frequency. The spectrum of the current induced in the cabin wire by the modified fuselage current pulse is shown in Figure B-1 by the line marked "modified pulse." The almost perfect agreement with the measured data is probably fortuitous and should not be taken too seriously.

The important conclusions from Figure B-1 are several. First, the signals induced in the aircraft wiring are strongly dependent upon the leading edge of the pulse which determines the high-frequency content of the source spectrum. Second, the normal apertures in an all-metal aircraft are adequate to cause substantial signals to be induced in internal wiring, and replacing metals with composites will only make matters worse. Finally, the experimentation with k-streamer current pulse form offers a demonstration for why some of the pulses in the flash of Figure 4-3 produced currents in the cabin wire and others did not. A fast leading edge on a particular pulse would result in substantial wire currents.

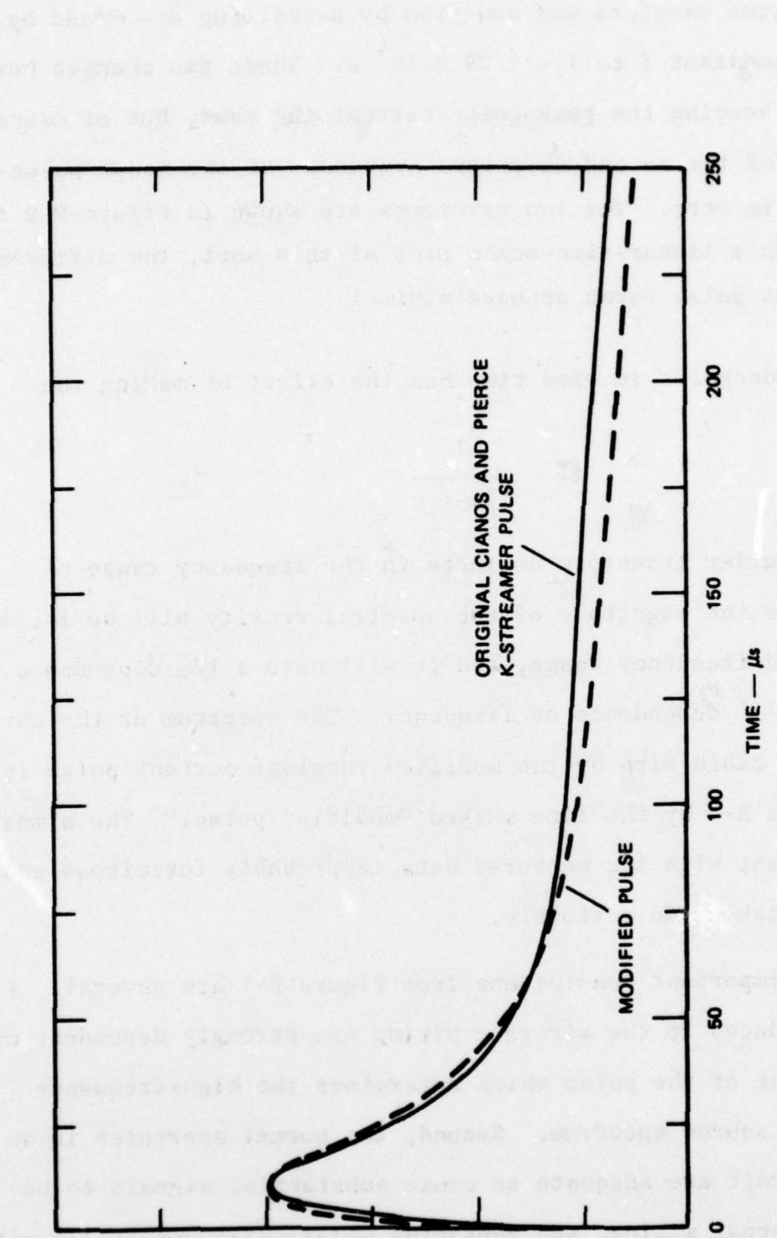

FIGURE B-2 COMPARISON OF K-STREAMER CURRENT MODELS USED IN CABIN WIRE CURRENT CALCULATIONS

These results point out the need for monitoring skin currents on future flight tests if transfer functions to the interior are to be determined. The results also point out the need for accurate information on k-streamer waveforms. The data available to date depend upon inferences from indirect measurements of these pulses. In particular, it would be desirable to develop statistical descriptions of rise time, duration, peak current, etc., of the sort that Cianos and Pierce have done for cloud-to-ground strikes.

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The authors wish to acknowledge with gratitude the contribution of numerous individuals, both co-workers at SRI and people associated with other organizations, without whose participation the program would not have been possible.

D. D. Arabian of NASA JSC initiated the flight test program and acted as principal investigator.

Co-workers at SRI who made substantial contributions to the program include G. R. Hilbers, who was responsible for the assembly of a working spectrum analyzer system on very short notice and also participated in the flight testing. E. F. Vance carried out the analyses of lightning signal coupling presented in Appendix B. R. L. Warner and W. Wong participated in the flight testing and took care of equipment maintenance during the test program. R. Martin worked with G. R. Hilbers to get the instrumentation out on time. S. Blumberg was originally to spend all of his time on data reduction but was pressed into service as a flight test observer on many of the flights.

Major J. Mansur, of AFFDL initiated the Air Force participation in the program and, with Dr. J. Corbin, followed its progress to its conclusion. Capt. J. T. Dijak participated in all of the flight tests involving the AFFDL transient digitizer. V. Mangold, also of AFFDL, participated in the planning and implementation of the transient digitizer portion of the flight tests.

C. Jenkins of the JSC resident office at NASA KSC assisted with the field meter data-reduction program associated with the flight

tests and provided outstanding service in securing crucial equipment and maintenance facilities during the test program.

W. Durett and his TRIP staff provided the impetus for establishing a test program at KSC and were of great help in securing the numerous items of support and communication necessary for a successful program.

Deserving particular recognition were the NASA Ames personnel associated with the Learjet test aircraft. R. Mason and his positive approach to dealing with experimenters made the entire program flow smoothly and efficiently. The ground crew was particularly responsive and attentive to the requirements of the experiment. The experimental test pilots were of the highest caliber. They familiarized themselves with the technical requirements of the experiment and operated the aircraft in such as way as to generate the requisite data as efficiently as possible.

Dr. E. T. Pierce of NSSL, with his depth of experience with lightning, provided insights that proved extremely valuable as the program progressed.

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